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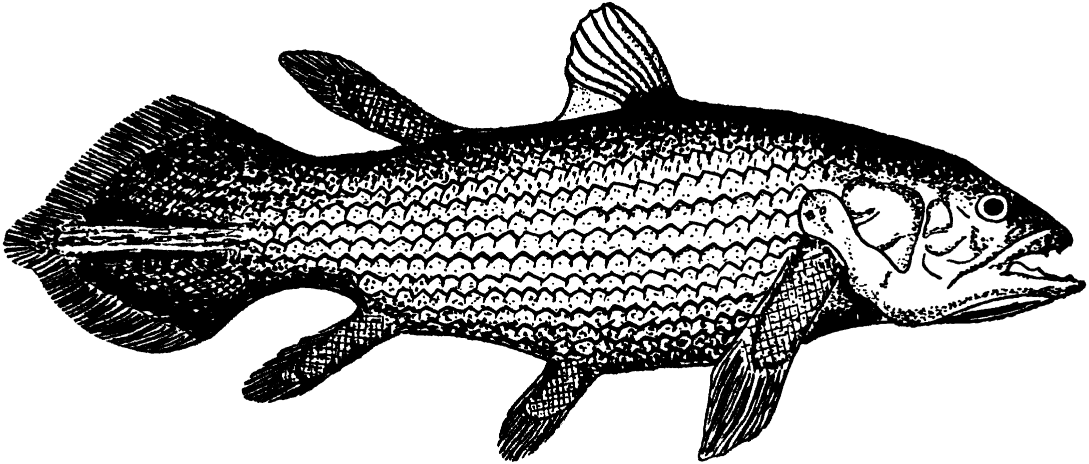

The "living fossil"—*Latimeria*—a fish dredged up off South Africa by deep-sea fishermen and belonging to a group previously thought to have been extinct for 60,000,000 years. It was more than five feet long, steely blue in colour and weighed 127 lb.

"REASON WHY" SERIES

EVOLUTION

By

CHAPMAN PINCHER, B.Sc.

Illustrated by the Author

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FOREWORD

THERE are many books which adequately present the evidence for the existence of evolution but I know of none which also explains, in terms easily understandable to general readers, how evolution is believed to have happened.

This book tries to present both facets of the fascinating story. The accent is on the mechanisms whereby animals and plants have evolved—and, of course, are still evolving. But the general evidence is first dealt with to a degree sufficiently detailed for most people.

I have repeatedly stressed in the book that though the concept of evolution cannot reasonably be doubted there is still controversy as to how the process took place.

To present every academic argument would confuse the reader so I have put forward what I consider to be the most acceptable synthesis.

CHAPMAN PINCHER.

FARNHAM, SURREY.
January, 1950.

CONTENTS

SECTION PAGE

AUTHOR'S FOREWORD 5

I. THE COURSE OF EVOLUTION FROM LIFE'S ORIGIN TO MODERN MAN 13

II. INHERITANCE AND VARIATION—THE "RAW MATERIALS" OF EVOLUTION . . . 73

III. EVOLUTION IN ACTION—THE INTERPLAY OF HEREDITY AND ENVIRONMENT . . . 144

APPENDIX 175

GLOSSARY 186

TABLES 190

LIST OF BOOKS 196

INDEX 197

LIST OF ILLUSTRATIONS

FIG. PAGE

The "living fossil"—*Latimeria*—a fish dredged up off South Africa by deep-sea fishermen *Frontispiece*

1. Part of the earth's crust in profile . . . 15
2. A slab of rock containing the fossil remains of a bird (*Archæopteryx*) 16
3. (A) Part of the surface of a tulip leaf much magnified to show the breathing holes. (B) Part of the surface of a fossilised leaf about 300 million years old 17
4. Two fossil shells of the same genus (*Paludina*) . 22
5. The lower left forelimbs of six fossil horses arranged in order of decreasing age 23
6. The carrion crow and the hooded crow . . 25
7. The distribution of the two crows . . . 26
8. Three species of lung fishes 30
9. Where the three genera of lung fishes are found . 31
10. An *Amœba*, much magnified 33
11. A strip of jellyfish tissue magnified . . . 33
12. Four backboneless animals 34–5
13. *Amphioxus* 36
14. Frog tadpole and young fish 38
15. The chief characters of the five groups of backboned animals 40
16. A one-celled plant 42
17. Simple algas 43
18. A trilobite 45

FIG. PAGE
19. The lamp-shell, *Lingula* 46
20. An armoured fish 47
21. A horseshoe crab 47
22. One of the earliest known land plants . . 48
23. Reconstructions of the sort of trees which made up the forests of Carboniferous times . . 49
24. An early amphibian 50
25. Diagrammatic head-on view of an early amphibian . 50
26. Reconstruction of *Scutosaurus* 51
27. *Diplodocus* 53
28. *Stegosaurus* 53
29. A long-tailed flying reptile 54
30. The oldest known fossil bird 55
31. One of the last of the dinosaurs . . . 57
32. *Brontotherium* 60
33. The digestive systems of a frog and a man compared 62
34. The useless muscles of the human ear . . 63
35. Skull of a chimpanzee 66
36. Palates of modern man, Dartian, and chimpanzee . 66
37. Skull of a female "Pekin-man" . . . 69
38. Front view of the skull shown in Fig. 37 . . 69
39. Skull of a Neanderthal man 70
40. Crystals of a virus 74
41. How an *Amœba* divides 76
42. A human egg magnified to show the structure . 77
43. The 48 chromosomes in a fertile human egg . 78
44. A single chromosome magnified to show the separate genes 78

FIG. PAGE
45. Section through a human ovary 80
46. A human sperm 81
47. Division of a fertilised egg 82
48. Division of a chromosome gene by gene . . 83
49. Ovary cell undergoing division 86
50. The effect of random assortment of chromosomes at germ-cell formation 87
51. Imaginary pair of chromosomes 89
52. Model of a chromosome 89
53. The inheritance of human eye-colour . . . 93
54. Mating of two blue Andalusian fowls to give a second generation 96
55. The mating of single- and rose-combed fowls . 98
56. The effect of mating two rose-combed fowls . 99
57. Result of crossing a red spotted cow with a uniformly black bull 101
58. Result of crossing two beasts impure for black and uniform coloration 102–3
59. Ovary cell dividing by the chromosome reduction process 105
60. The effect of crossing an Angora buck with an English doe 107
61. Explanation of the result of mating two impure English rabbits 108
62. Ovary cell of a hypothetical insect 109
63. Crossing over of genes 112
64. A female *Drosophila* 113
65. Part of a giant chromosome of *Drosophila* . 116
66. The recombination of genes following breakage of a chromosome 126

FIG. PAGE
67. The effects of a lethal gene in mice . . . 132
68. Body cells of female and male *Drosophila* flies . 136
69. How sex is determined in *Drosophila* . . 137
70. An atom of helium 175
71. An atom of uranium exploding by throwing out a "bullet" made of two protons and two neutrons 176
72. The rhythm of the Ice Ages 183

SECTION I

THE COURSE OF EVOLUTION FROM LIFE'S ORIGIN TO MODERN MAN

What is meant by evolution?

Evolution is the process whereby a simple thing develops through a series of steps into something more complicated.

The development of the aeroplane is an example of evolution. The modern airliner—a very complicated machine—has slowly *evolved* through many thousands of gradual improvements from the relatively simple flying machine built by the Wright brothers. The motor-car, the ship, the typewriter and the fountain pen have also undergone such a gradual evolution.

It is, of course, a general rule that a complicated manufactured object has been preceded by something simpler. Biologists believe that this rule also applies to living things—to all plants and animals, including ourselves. A complicated organism like a dog or a cabbage has arisen from ancestors which were of simpler construction.

Now a dog and a cabbage are very much more complicated than any aeroplane. So we should expect their evolution to have taken longer. We shall see that all the evidence suggests that it has taken many millions of years in each case.

This idea of *organic* evolution—the evolution of living things (which is what is meant by the word " evolution " throughout this book)—is directly opposed to statements made in Genesis. According to the Old Testament, God made all the animals and plants in three miraculous days and it is inferred that each organism has come down to present times unchanged.

This belief of *special creation* is no longer held by progressive Churchmen who have found it impossible to ignore the overwhelming evidence in favour of evolution. All they have had to do to harmonise their religious teachings with the acceptance of evolution is to interpret Genesis less literally.

For the facts supporting evolution as now understood in no way deny the existence of God. They show how life has evolved but do not explain why.

What composes the "overwhelming evidence" in favour of evolution?

The greater part of this book will be taken up with the presentation of this evidence but at this stage we can briefly discuss the most convincing facts on which the belief in evolution rests—the record of *fossils* preserved in rocks.

We know that the crust of the earth began to solidify from a molten state to form rocks something like 3,000 million years ago. Deep down these rocks must be much as they were when they first cooled, but the superficial layers of the crust have been entirely changed. Over the centuries inexorable erosion by wind, water, shifting ice and fluctuating temperature ground the surface rocks to minute particles. Swept away by rivers these were deposited in the seas. In this way the primal rocks which formed the floor of the first oceans were covered with great layers of sediment.

Then as heavings of the crust lifted these ocean floors high into the air the silt settled and dried out to form friable rock. Often before the ceaseless agents of erosion had completely worn away this new covering a further massive movement of the crust took it back below sea-level. So on top of one layer of sedimentary rock another layer—as like as not of a different mineral nature—began to collect. By its weight it compressed and hardened the first.

In this way the earth's original surface has been replaced by successive layers of rocks of different constitution and of variable thickness laid down one upon the other, like so many coats of paint. But rarely have these layers remained flat and even. They have been crumpled, sliced, burnt and sometimes turned completely over by landslides and volcanic action. Because of this there are many places in the world where the rock layers slant to the surface so that their nature can be studied and their history deduced (Fig. 1). This is very much the case in Britain. Thus in a coast-to-coast journey from say Dover in Kent to Bangor in North Wales, a traveller moves over successively older rocks differing widely in composition. All this is of the greatest importance to the study

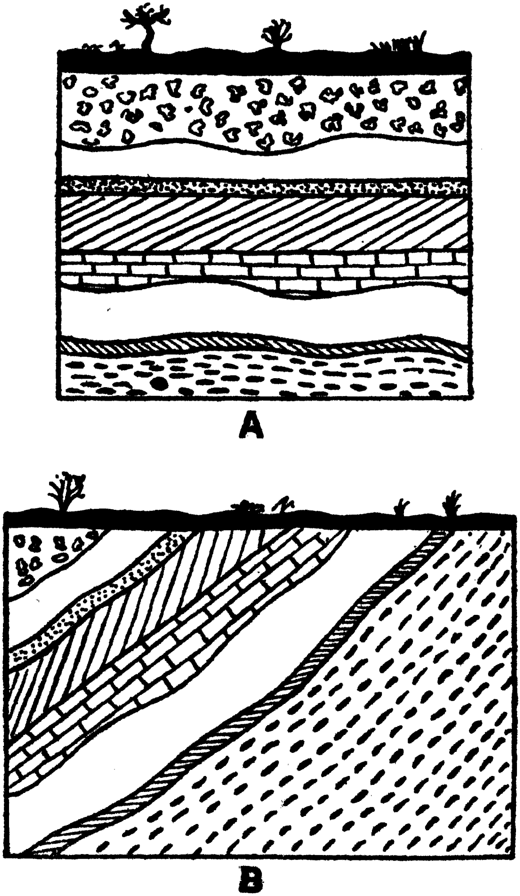


FIG. 1.—Part of the earth's crust in profile, showing (A) successive layers of different rocks, and (B) how a landslide can make this layering visible at the surface.

of evolution, for embedded in these rocks are relics of long-dead organisms preserved in the form of fossils.

A fossil is anything dug out of the earth which represents the remains of a dead plant or animal. Some fossils are simply imprints formed when the dead bodies of organisms were squashed into the rock whilst it was still soft. The substance of the organisms eventually decayed away but its impression was fixed forever as the rock hardened.

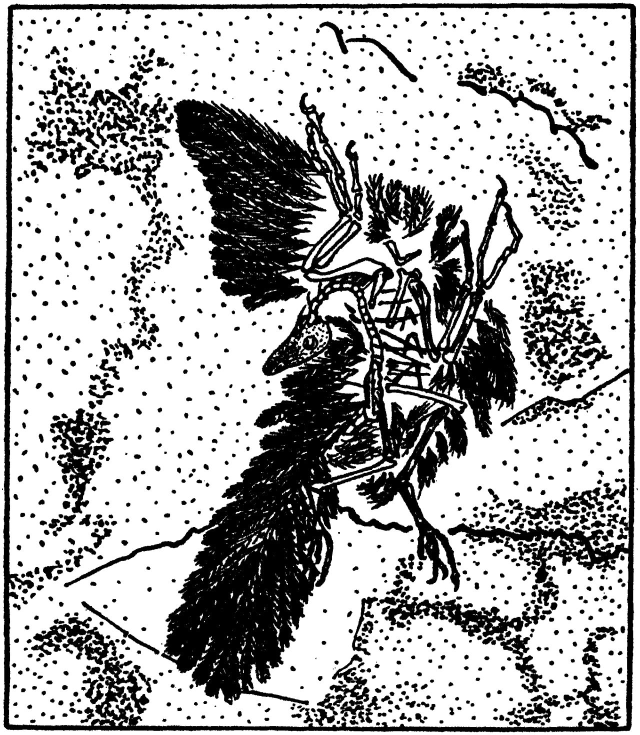


FIG. 2.—A slab of rock containing the fossil remains of a bird (*Archæopteryx*) which died 150 million years ago when the rock was formed.

In other cases the original bone has been preserved—though in a delicate and friable condition—by being covered with dry sand or volcanic ash. This is especially true of the bones of mammals which, being in superficial rocks not subjected to much pressure, are often almost as fresh as bones of historic age. More often, however, the hard parts of an animal or plant become entirely replaced by mineral matter—lime and silica in particular—being thereby changed into stone. Fig. 2 shows a slab of rock from Germany bearing the fossilised remains of a bird. The individual bones have been completely petrified and the outlines of the feathers are faithfully imprinted.

Throughout the world there are scattered rocks so rich in fossilised animal remains that they are called bone-beds. Some of them represent quiet eddies where the carcases of dead animals washed down by flooded streams collected and became covered with a protective layer of silt. Others represent sudden catastrophes on a mass scale. The great bone-beds of the Island of Samos, for example, seem to be the result of a volcanic eruption which killed thousands of animals and covered them with a layer of ashes.

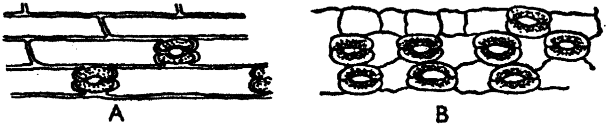


FIG. 3.—(A) Part of the surface of a tulip leaf much magnified to show the breathing holes. (B) Part of the surface of a fossilised leaf about 300 million years old.

In the case of many plant fossils the replacement of the tissues by mineral matter is so perfect that even microscopic structures remain. Fig. 3(A) shows the skin of a living leaf magnified to show the special holes through which breathing and evaporation occur. The magnified surface of the fossil leaf (about 300 million years old) shown in 3(B) proves how faithfully the finest detail can be preserved.

Some fossils represent types of animals and plants which are still alive today. But most of them are remains of organisms which are quite extinct. Within historic times animals like the dodo and the American passenger pigeon have died out because they were unable to cope with new circumstances which beset them. The geological record shows that this extinction process has been a natural consequence of evolution since life began.

The form of a few long-extinct animals is known to an exceptional degree because their mummified carcases have been unearthed. Some of them contain identifiable remains of the original stomach contents, thus providing evidence of diets. Even fossil eggs 80,000,000 years old and the fossilised droppings of some creatures have been discovered.

By methods which will be described later (see Appendix) scientists have been able to date the various sedimentary rock layers—and therefore the fossils they contain—with what is believed to be reasonable accuracy.

The result of their study is that the history of the earth's crust since the time it first solidified has been divided into 17 main periods. They have been given the names shown in Table 1. Thus the oldest period believed to be between 2,000 and 3,000 million years old is called the Archæozoic period. The second oldest period—thought to have lasted from the end of the Archæozoic until about 550 million years ago—is called the Precambrian and so on to the present period which has been going about 20,000 years and is therefore called (by geological standards) Recent. These names are rather confusing so in this book we shall refer to the periods by the numbers shown in Table 1 as well as by the names, e.g. Silurian (No. 5), Eocene (No. 12).

The different periods, which were fairly sharply demarcated by climatic changes, lasted for varying lengths of time. Thus the Cambrian (No. 3) is believed to have lasted about 70 million years whilst the Permian (No. 8) endured for less than half as long. (The date figures given in this book are not mere guesses: they are based on factual evidence provided by the critical studies of chemists and geologists. They cannot be exact dates, however; the length of the periods makes a completely accurate estimate of their age impossible. But they can be taken as providing a reasonable assessment of the geological time-scale.)

The changes in successive climates were often very severe. For example, the warm swampy Carboniferous period (No. 7) with its lush vegetation which gave rise to the coal deposits was followed in Britain by long dry eras characterised by intermittent periods of intense cold. These changes may have been the result of massive alterations to the shape of continents, but they were more probably due to fluctuations in the earth's orbit round the sun. Whatever their cause they certainly had immense effects on the life of the times.

The main fact that emerges from a wide study of fossils is this :

All the oldest fossils (from the Precambrian rocks (No. 2) are of organisms which were of very simple structure—things like sponges and seaweeds. There are no remains among them of any of the animals and trees common today. Then as we pass through the layers of younger rocks above we find fossils of increasingly more complicated organisms. Thus in rocks of No. 5 period we find the remains of simple fishes ; in period No. 7 rocks the fossilised bones of reptiles occur ; we strike bird and mammal fossils in period 10 ; in the uppermost layers the first signs of man appear.

The significance of all this is inescapable. It can only mean that the first living things were simple in structure and that the rest—including man himself—have arisen by gradual evolution during the last 2,000 million years.

As we shall see later the detailed evidence of the fossils enables us to put a much finer point on this argument.

Have there been any cases where organisms discovered as fossils and thought to be extinct have later been found alive ?

There have been two such cases within recent years.

In 1938 trawlermen fishing off South Africa dredged up a six-foot-long creature which proved to be a fish of a type well known from fossils and believed to have become extinct some 60 million years ago (see frontispiece). The event was a biological bombshell as dramatic as if a *Brontosaurus* had been captured in the South American jungle.

A few years later almost the same thing happened with respect to a fossil tree. Up to that time the type of redwood trees called *Metasequoias* were known to science only from fossil remains and were thought to be quite extinct. But in 1945 botanists found nearly a thousand *Metasequoias* alive in a remote Chinese province. Seeds were distributed to botanic gardens and some young seedlings of this "extinct" conifer are now growing at Kew.

It is more than likely that other organisms thought to be long extinct are alive in the depths of the seas and in the wildernesses of Asia and South America.

How were fossils explained before the theory of evolution had been developed?

Up to the middle of the nineteenth century fossils were generally believed to be the remains of animals which had perished in the Great Deluge. (The idea of a Universal Deluge —a flood covering the entire surface of the earth—is incompatible with the precise statement given in Genesis that "fifteen cubits upward did the waters prevail". Such a 22-feet flood might swamp most of the flat country of Iraq, where Noah apparently lived, but to believe that it could cover the entire earth's surface is absurd.)

Some scientists later interpreted the geological record as showing that all living things had been completely extinguished several times in the earth's history and had then been re-created in a different form.

There is no evidence for this belief in a series of separate miracles and there is much evidence against it.

There seems to be no doubt that under existing earthly conditions life can spring only from existing life—that is, organisms can arise only as the offspring of other organisms. No plant or animal can arise spontaneously from any combination of dead materials. Such a *spontaneous generation* must have happened in the beginning—about 2,000 million years ago according to the fossil record—but there is no evidence to show that it has ever happened since. It may be that the peculiar climatic circumstances in which inanimate materials took on the properties of life lasted only a short time and have never been repeated.

The idea that each kind of organism was separately created from inanimate materials becomes absurd when fully explored. Consider the different races of men, for instance. Are we to believe that Hindus, Hottentots, Englishmen and Eskimos were all separately created? If not and we accept instead the belief that they are all related, being derived from some ancient ancestral stock, then we should find no difficulty in accepting the main principle of evolution—that all living species have an ultimate common ancestry.

Just what do you mean by this word "species"?

When from a study of their structure and habits it is seen that two organisms—plants or animals—are not closely related they are said to belong to different *genera*. Each genus is given a distinctive scientific name. Thus the dog belongs to the genus *Canis* and the cat to the genus *Felis*: the cabbage belongs to the genus *Brassica* and the plum tree to the genus *Prunus*.

When two organisms are obviously closely related but still show marked inherited differences they are placed in the same genus but are graded as different species. For example, the cat is *Felis domesticus* whilst the lion is *Felis leo*: the plum is *Prunus domestica*, the damson *Prunus inistitia*.

Normally an organism will breed successfully only with another organism of the same species. Different species of animals rarely attempt to mate and if they do the result is usually fruitless. In captivity two species of the same genus may be induced to interbreed thereby giving rise to *hybrids*. Thus the mule is a hybrid between the horse and ass—two distinct species of the genus *Equus*: the tigon is a hybrid between the tiger and the lion—two distinct species of the genus *Felis*. It is very difficult to get hybrids between species of different genera even with the help of artificial insemination. The cat and the dog cannot be made to interbreed, for instance, though widely different plants may sometimes be crossed successfully.

According to the theory of evolution each species alive today, although it is normally a quite separate breeding group, has arisen by gradual development from some pre-existing species. This means that from one species another type of organism arises which breeds only with organisms like it and in other ways is sufficiently different from its ancestors to be classed as a separate species. Only in a few cases—chiefly plants—are the ancestral species of existing species still alive. In most cases the origin of one species from another has been so gradual that the ancestral forms are extinct and known only as fossils.

Are there any cases where the fossil record is complete enough to show definitely that one particular species has evolved into another?

There are several such cases. Consider for instance the two fossil shells shown in Fig. 4. They are sufficiently different to be classed as quite distinct species. Yet in the rocks can be found fossil specimens which bridge the gap between them in a series of almost insensible steps.

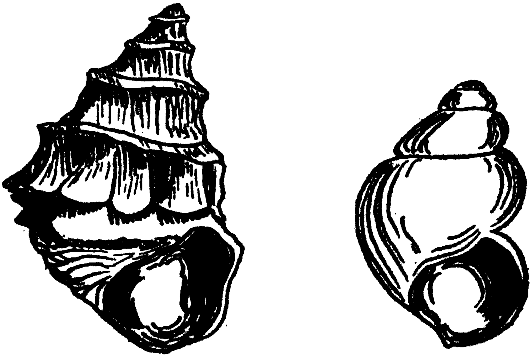


FIG. 4.—Two fossil shells of the same genus (*Paludina*). Other specimens can be arranged to form a series linking these two shells by almost indiscernible steps.

In some cases the record is so complete that a whole series of species can be linked in this way. The fossil remains of the ancestors of the modern horse provide such a series. This is best illustrated by focusing attention on some small part of the fossilised skeletons. We shall concentrate on the forefoot.

The earliest definitely known ancestor of the horse—called *Eohippus* (the dawn horse)—lived about 65,000,000 years ago in early Eocene (No. 12) times. It was about the size of a fox terrier and had a hand shaped as shown in Fig. 5(A). It will be seen that there were four perfect fingers each with a nail and where we should expect to find a thumb there was

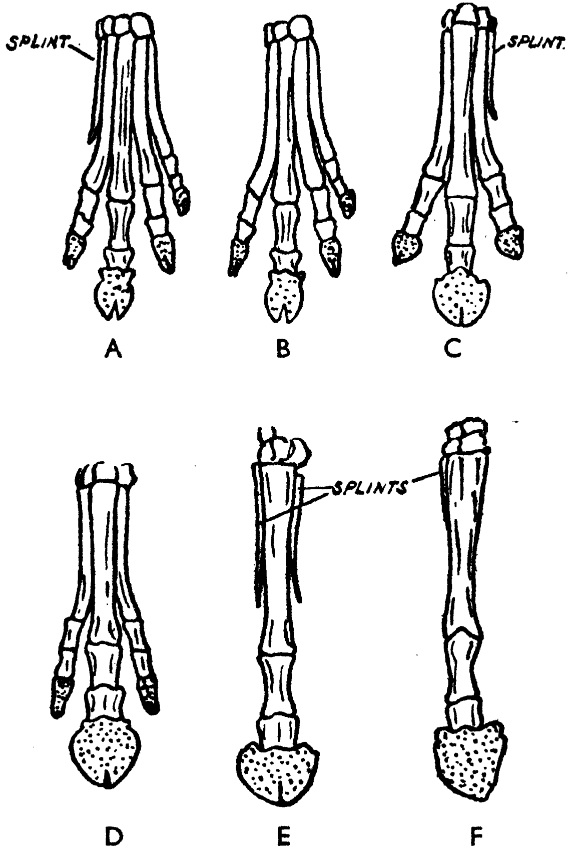


FIG. 5.—The lower left forelimbs of six fossil horses arranged in order of decreasing age and showing the gradual elimination of all the fingers except the middle one.

a thin bony splint. Earlier fossils tell us that the first land animals had the thumb completely formed. It seems then that during the development of the animals which gave rise to *Eohippus* the thumb had gradually been reduced to a useless sliver of bone.

In slightly higher and therefore later Eocene rocks are found the fossilised remains of another early horse—the mountain horse *Orohippus*. Fig. 5 (B) shows the skeleton of its fore-foot. The thumb had completely disappeared. A little higher still in the Eocene rocks occur the skeletons of *Epihippus*, a slightly larger horse. Its hand was similar to that of *Orohippus* but the middle finger was proportionately bigger and had a more prominent nail.

In rock layers laid down in the next period—the Oligocene (No. 13)—we find the fossil relics of *Mesohippus* (Fig. 5 (C)) in which the little finger was reduced to a splint and the middle finger was clearly carrying most of the weight. *Miohippus* found in the upper layers of the Oligocene rocks had the vestige of the little finger still further reduced to a knob and the middle finger was even more predominant with the nail becoming more and more like a hoof.

How this record continues through younger and younger rocks is shown by the remaining sketches in Fig. 5. They take us through to upper Pliocene (No. 15) times when the immediate ancestors of the modern horse—members of the genus *Equus*—arose.

We started with a hand in which there were four complete fingers, each with its nail, and a vestige of a thumb. We end with an elongated structure formed of a single enlarged finger with its huge nail serving as a hoof.

It is not possible to explain the geological distribution of these fossil hands in any way except as a progressive series.

This conclusion is supported by a similar study of other parts of the skeletons.

Are there any cases where this process of one species giving rise to another is known to be going on now?

The origin of new species is of course much more clearly shown by fossils which record changes covering many millions of years. But there is strong evidence that the process is still in action among living organisms. The two types of crows found in Britain—the carrion crow and the hooded crow—provide what appears to be a straightforward case.

The two birds are easy to distinguish. The carrion crow is uniformly black whilst the hooded crow has a grey back and underparts (Fig. 6).

They breed true to type—the offspring of two hooded crows are like their parents and never all black like the carrion crow. Similarly two carrion crows never give rise to birds with the hooded pattern. But as regards their size, internal structure and general habits they are identical. Moreover they can interbreed and often do so in those places like the southern Highlands of Scotland where both types of crow occur.

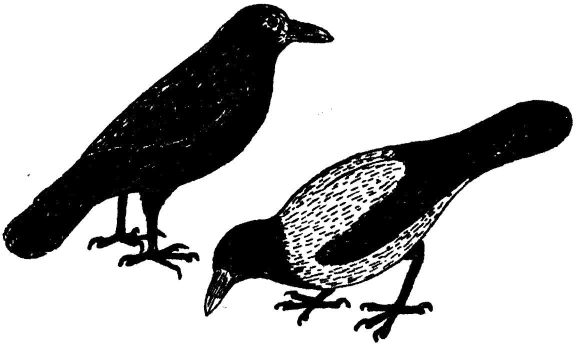


FIG. 6.—The carrion crow (left) and the hooded crow—two species with a common ancestry.

Some ornithologists class the two birds as different species : others maintain they are no more than varieties of one kind and not yet sufficiently different to warrant classification as separate species. But few doubt that both birds have arisen from a single species since late Pleistocene (No. 16) times.

These two crows also illustrate a principle of the greatest importance to the study of evolution. Their distribution shows quite clearly that the birds are each adapted to life in different environmental circumstances. No mechanical barriers such as high mountains or oceans separate the two types of crows in Britain. Yet for the most part they inhabit well-defined territories. Thus the hooded crow is abundant in the Scottish Highlands but uncommon in southern England, whilst the reverse is true of the carrion crow. Both birds are strong enough to fly the Irish Sea and occasionally do so. Yet, as Fig. 7 shows, the hooded crow is a resident bird in Ireland breeding in every county whilst in England it is no more than an autumn and winter visitor. The carrion crow, on the other hand, is distributed throughout England and reaches Ireland only as a rare vagrant.

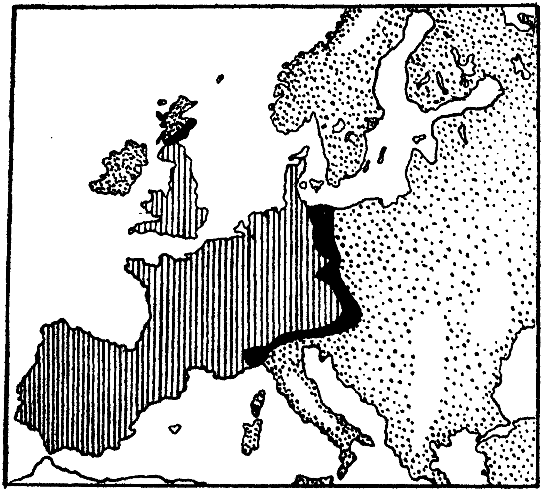


FIG. 7.—The distribution of the two crows. The striped regions mark the range of the carrion crow: the spotted region the range of the hooded type. The black patches show where the two crows overlap in range and sometimes interbreed.

The broad principle that each species of plant and animal is fitted to live under particular conditions is self-evident. Coconuts will not grow in the Scottish Highlands and reindeer cannot live in the Burmese jungles. But the close limits within which certain organisms are restricted is not so generally appreciated. The crows show this to some extent but certain plants and animals are so closely dovetailed with a local set of conditions that they cannot live anywhere else. The Lulworth Skipper butterfly is restricted to a few areas in Dorset and South Devon all within a few miles of the coast: the fungus *Pyronema* can grow only on soil which has been burned.

We shall see that the degree of adaptability possessed by an organism largely determines its evolutionary fate: the tighter the limits in which it can live the poorer its chance of survival in a changing world.

The two crows have become noticeably specialised to different conditions within the last 500,000 years or so. The odds are that the differences between them will become intensified. For once two groups of similar organisms form independent breeding communities, in different environments they tend to pursue increasingly divergent lines of evolution and eventually cease to be fertile with one another.

Is it the general belief then that once a number of animals forms an independent breeding group—a " closed shop " as it were—they are likely to evolve into a new species?

Yes, and it seems to be true for plants too. We shall see later that the formation of such " closed shops " is one of the most important factors in evolution. For a set of good examples all we need to do is to take another look at the fossil horses.

So far we have considered only the *vertical* distribution of fossils—the depth of their position in the rocks—which, as we have seen, gives a fair estimate of their age. Their *horizontal* distribution can also be studied. This tells us that just as in the case of living animals the fossil creatures were each restricted to certain parts of the world. Thus some fossils are found only in Australia: others are restricted to Africa and so on.

In those cases like the horses where the fossil record is well studied we can see clearly how over millions of years a small group of creatures arising in one locality slowly multiplied and spread over great areas of the earth. We see too that as they went, colonising new regions, they gave rise to new species.

Searches by geologists in many parts of the world have led to the belief that the first animals clearly recognisable as the ancestors of modern horses arose in North America. The earliest of them—*Eohippus* (also sometimes called *Hyracotherium*), the creature we said was about the size of a fox terrier—has been found in Lower Eocene (No. 12) rocks in North America and Europe. The next four higher types in the evolutionary series however—*Orohippus, Epihippus, Mesohippus* and *Miohippus*—are found only in North America. It is reasonable then to suppose that members of the *Eohippus* species wandered to Europe across the dry land, which then connected that continent with America, but petered out there without giving rise to any important new lines of development, whilst in the home country evolution progressed.

To carry the story further, remains of horses generally similar to *Miohippus*, but sufficiently different in detail to be classed as belonging to different species, have been unearthed in South America. These suggest that late in the Oligocene (No. 13) period horses of the *Miohippus* type wandered southwards away from the main American herds and formed separate breeding groups which, over a long period of years, developed into distinct species.

Later on more offshoots of the main horse stocks still centred in North America wandered into the southern half of the continent, whilst others migrated into Asia and Europe, moving over land that has since been submerged forming the Behring Straits. There they too slowly developed into new types.

It seems certain from the fossil record that all these early invasions of Europe and South America proved to be failures from the evolutionary point of view. Though the new colonies lasted for millions of years they eventually all died out without producing any forms which have persisted until the present day.

All existing creatures of the horse tribe are almost certainly descended from a group of horses which did not separate from the main North American stock until relatively recently in lower Pleistocene (No. 16) times.

Members of this group recolonised South America, Asia and Europe and were the first horses to reach Africa.

In those different environments they became cut off as independent breeding groups and gave rise to the zebras, asses, quaggas and modern horses of today.

It is impossible to explain the geological evidence in any other way linking so perfectly, as it does, with the geographical distribution of the living horses.

It is an odd and so far unexplained fact that after the last great migration of the horses from North America the parent stock rapidly died out. Horses also became completely extinct in South America. For many thousands of years there were no horses whatsoever in the America continent. They were reintroduced there from domesticated stocks by the Spanish Conquistadores in the sixteenth century.

Only in Africa and Asia are truly wild horses found today.

Does the geographical distribution of living animals in general fit in with the theory of evolution?

Yes, and in many ways strongly supports it. In the first place it strengthens the belief that similar species of animals have had a common ancestry and have not arisen independently.

There are some islands known to have been severed from any mainland for many millions of years whose fauna has been closely studied. Madagascar and the Galapagos Islands off the coast of Ecuador are good examples. From the general principles of evolution we should expect that some of the animals living on these islands when they were cut off from the mainland would in the course of time give rise to new species. We should further expect these species to be slightly different from any which might evolve at the same time from the mainland stocks because of the different environmental circumstances affecting the separated populations. Once such a divergence in evolution has been established it persists and intensifies. So after a lapse of many millions of years we would expect each island to have groups of related species which, because of the perpetual water barrier, would be found nowhere else in the world.

These expectations are fully justified by the facts. Of about 260 species of birds found in Madagascar 50 per cent occur nowhere else: about 95 per cent of the reptile species on the Galapagos Islands live only there. The argument also applies to plants. Thus more than 80 per cent of the plants found on the Hawaiian Islands, which have also long been isolated, are found nowhere else on earth.

Clearly if these closely related organisms had each arisen independently as a result of special creation there is no reason why they should all be restricted to the same locations.

The fundamental principle that the different species of organisms have arisen at widely different periods in time and were not all created simultaneously is also supported by the study of the geographical distribution of animals and plants.

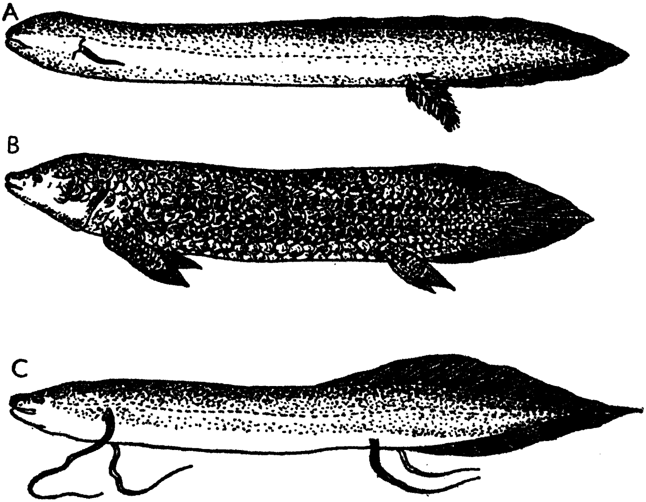


FIG. 8.—Three species of lung fishes from South America (A), Australia (B) and Africa (C).

To illustrate this point we will consider two groups of animals—the lung fishes and the kangaroos.

Lung fishes are strange creatures normally breathing by means of gills like other fish but also possessing a lung-like organ which enables them to get oxygen from the air if they are left high and dry.

There are three genera of lung fish all living in fresh water and, as can be seen from Fig. 8, clearly close relatives.

It is unlikely that they ever dwelt in the sea, for the "lungs", which keep them alive when the rivers they inhabit dry up, would be unnecessary there. Yet the three types live in different countries completely cut off from one another by thousands of miles of ocean (Fig. 9). One of them inhabits South American swamps. Another is found in rivers in Queensland. The third lives in stagnant pools in tropical Africa.

From general evolutionary evidence we should infer that these three similar creatures had a common origin. If so how did they become so widely dispersed?

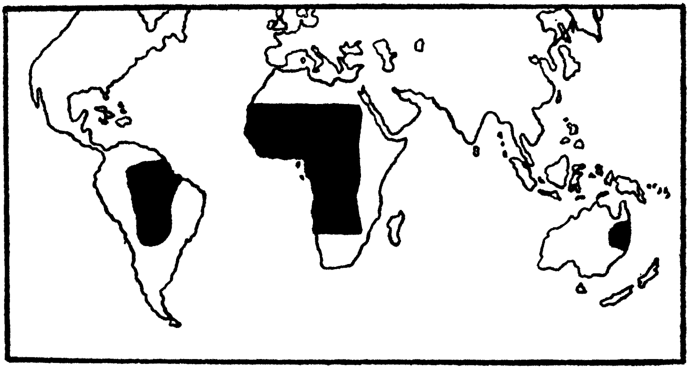


FIG. 9.—Where the three genera of lung fishes are found.

There is only one simple explanation. These fishes are the sole survivors of an ancient and once abundant race which from their place of origin spread throughout the fresh waters of the world at a time when Australia and the other great continents were linked by land.

Now let us look at the kangaroos. Kangaroos occur naturally only in one region of the world—Australia and its neighbouring islands. All their near relatives are also confined to that area. This is surprising, for kangaroos are hardy creatures and could thrive in most continents. How then can we explain their restricted distribution?

The simplest explanation is that the kangaroos evolved in Australia *after* it had become separated from Asia. They were therefore unable to spread to other lands.

If these interpretations are correct then the kangaroos must have evolved at a later date than the lung fishes.

That they are correct is amply confirmed by fossil and general geological evidence. The fossil record shows that about 180 million years ago in Triassic (No. 9) times lung fishes were common and widely distributed. Fossil kangaroos do not occur until the Eocene (No. 12) period many millions of years later and so far they have never been found outside Australasia. At the same time geologists are satisfied that Australia did separate from the mainland which later formed Africa and South America between the Triassic and Eocene periods—most probably towards the end of Cretaceous (No. 11) times. And there is the most significant fact that the later mammals—the land-dwelling carnivores and the rodents—never reached Australia until man took them there, though they colonised the rest of the globe.

There are many other equally convincing examples to support the principle that the different animals arose at different times.

Are there any other peculiarities about living animals which support the theory of evolution?

Yes. The most convincing is the fact that although there are millions of diverse species they fall naturally into a relatively few well-defined groups which form a series beginning with the simplest organisms imaginable and leading through ever-increasing complexity to man himself.

We will briefly consider these groups.

Representative of the simplest group is the *Amœba*—a creature about the size of one of the full stops on this page. As Fig. 10 shows. the *Amœba* is little more than a blob of jelly containing a specialised region called the *nucleus* and surrounded by an elastic wall. Yet it has all the properties of life—it breathes, feeds and reproduces its kind. And by sending out exploring fingers of the jelly, which is known as *protoplasm*, it actively moves about.

There are many thousands of organisms no bigger and little more complex than *Amœba*. The group they form is called the *Protozoa*.

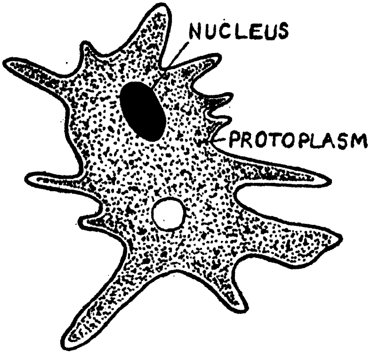


FIG. 10.—An *Amœba*, much magnified.

More complex than the Protozoa but very simple in structure compared with most animals we know are the sponges and the jellyfishes.

If we take a portion of either of these creatures and look at it under a microscope we see that instead of being composed of a continuous mass of protoplasm it is split up by partitions into tiny box-like units (Fig. 11). Each unit is called a *cell*, the partitions being the *cell-walls*. The sponges and the jellyfishes therefore represent a big biological advance on the *Amœba*, which is entirely made up of only one cell. By being *multicellular* they can be bigger and they can also be more efficient, for they can afford to set aside certain cells to do particular jobs. Thus in the jellyfish some of the cells are specialised just to capture food : others digest it : others work together to move the animal about and so on. In the *Amœba* one cell has to do all these jobs and obviously cannot do them so well.

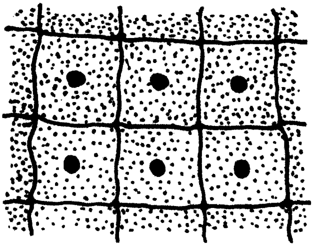
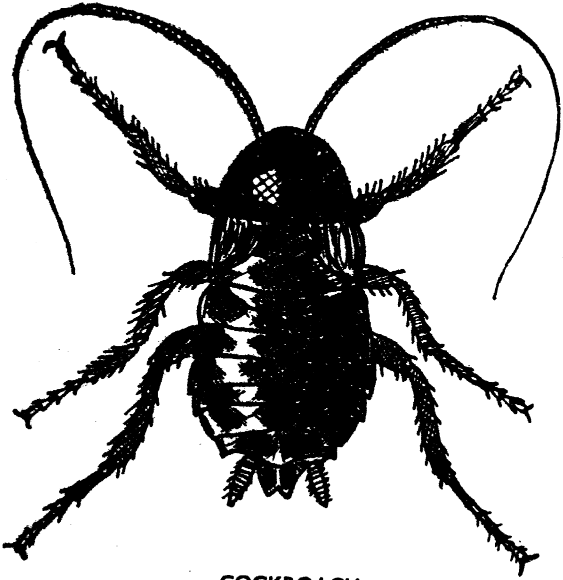


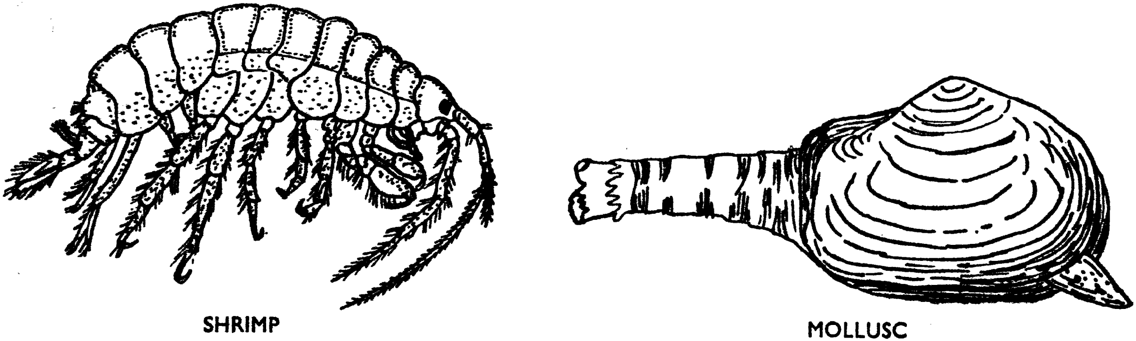
FIG. 11.—A strip of jellyfish tissue magnified to show the cells.

Being multicellular enables the jellyfish to retain a more or less definite shape but clearly there are limitations on the size such a creature can reach. If a jellyfish grew much bigger than a dinner-



COCKROACH

CRAB


SHRIMP

MOLLUSC

FIG. 12.—Four backboneless animals with a rigid outside skeleton.

plate it would collapse, for its tissues have no backbone to support them.

Several other big groups of animals share this backboneless or—to use the scientific term—*invertebrate* condition. Chief among them are the worms, molluscs (oysters, clams and snails), crustaceans (crabs, lobsters and shrimps) and insects. Some of them have solved the triple problems of retaining their shape, protecting themselves and providing a rigid fastening for their muscles to work on by developing a hard outer skeleton. Fig. 12 shows how this has been accomplished in different ways. Such devices have enabled some invertebrates—insects in particular—to become remarkably efficient in structure and complex in behaviour. In the sea, where the buoyancy of the water removes much of the need for strong skeletal support, they have enabled others—squids for instance—to grow to a large size. But on land they have obviously not provided the support which would allow a reasonable size to be attained. There are no really large invertebrates living on the land or flying in the air.

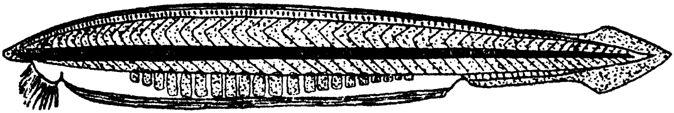


FIG. 13.—*Amphioxus*—a living link between the invertebrate and the backboned animals. The black rod is the primitive backbone.

This limitation on size is a fundamental obstacle to evolutionary progress for—as we shall discuss more fully later—a reasonably large brain is essential for advancement. A large brain needs a large head to contain it and this in turn requires a large body to move it about.

It is clear from a study of living animals that only those creatures with a backbone and the internal skeleton that goes with it have been able to overcome this size limitation.

There are in existence a few small animals which appear to bridge the gap between the invertebrates and the *vertebrates* (backboned creatures). The best-known of these—*Amphioxus*, which lives off sandy shores in the Mediterranean—is shown in

Fig. 13. Its three- to four-inch body is soft and tender but a long semi-rigid rod running from nose to tail gives it adequate support. The study of true vertebrates shows that the fully fledged backbone is built round just such a rod as this. So biologists have little doubt that in *Amphioxus* we can see a live demonstration of one of the earliest types of backboned animals. This view has been greatly strengthened by the discovery in Silurian (No. 5) rocks in Scotland of the fossilised remains of a creature very similar to *Amphioxus*.

The 70,000 or so backboned animals fall into five main groups—fishes, amphibians, reptiles, birds and mammals.

Of these the fishes are the least complex in structure and scope of behaviour. Their skeleton is relatively simple: they have no proper limbs; most of them breathe through simple structures called gills; and they are "cold-blooded", which means that their blood temperature varies with the temperature of the surroundings.

This last character is of the greatest consequence both to individual fishes and, from the evolutionary point of view, to the group as a whole.

The chemical actions that make up digestion, breathing and other essential processes are rapidly speeded up by increases in temperature and are correspondingly reduced by decreases. Since the body temperature of a fish varies directly with heat changes in the water outside, the animal is altogether at the mercy of climate. If the water gets very cold the body processes are so slowed down that the fish may become drowsy. If the water heats up the body chemistry may be accelerated to a dangerous level.

We know from the study of geology that there have been times of great temperature extremes—tropical and glacial periods alternating. Such circumstances must have profoundly affected the geographical distribution of heat-sensitive fishes then alive.

The amphibians, typified by frogs and newts, are an obvious advance on the fishes. Instead of fins they have well-developed arms and legs with fingers and toes. They can breathe in the air and walk on land.

Yet they are just as definitely like fishes. They arise from eggs laid in water and very similar to fish spawn. The young which hatch from these eggs—the tadpoles—are almost exactly like young fishes in structure and habit (Fig. 14). They swim like a fish, breathe by means of gills and even have lateral lines—rows of special sense organs one on each side of the body—which are peculiar to fishes.

Even when they have passed into the air-breathing stage, amphibians cannot keep away from water: they have to return there when they are mature to lay their eggs. They are cold-blooded like fishes too. Throughout their lives their degree of activity is controlled by the temperature outside.

This limitation is more serious for amphibians than for fishes, since temperature changes are more extreme on land. It means that frogs and toads cannot live at all in very cold climates. And in temperate countries like Britain they are forced to pass the winter in sleep.

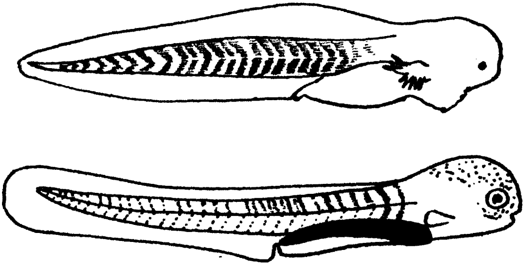


FIG. 14.—In the tadpole stage an amphibian such as a frog (*above*) resembles a young fish (*below*).

Reptiles, of which we may consider lizards and snakes as representative, are essentially land animals. Throughout their lives they breathe by means of lungs. Most of them have a covering of scales, which enables them to live in a drier atmosphere than amphibians can endure. They even lay their eggs on land. Some species, crocodiles and turtles for example, spend most of their time in water but it is clear from their structure and basic habits that they are essentially land animals which have taken to an aquatic life.

For three main reasons birds must be considered as a great advance on reptiles.

(1) They are warm-blooded, which means that they possess

a mechanism keeping their blood temperature—and hence their activity—at a particular level, irrespective of the temperature prevailing outside.

(2) The brain is proportionately larger.

(3) They take great care of their eggs and young.

There are also other ways in which the birds must be considered as more complex than the reptiles. Their hearts for instance, are more efficiently constructed—being divided into four chambers instead of three as in most reptiles—a structural modification which ensures a purer blood supply to the trunk. As a further example birds have their hearing mechanisms more efficiently protected than do most reptiles, the ear-drums being sunk in bony shafts—as they are in our ears—instead of being exposed in the skin surface, as they are in snakes for instance.

At the same time there are clear-cut resemblances between the two groups. Both types of animal lay large yolky eggs. There are similarities in the skeleton and internal structure. There seems to be a relationship between the feather and the reptilian scale.

The last great animal group, the mammals, shares with the birds the advantage of being warm-blooded. In other ways it is much more advanced.

In the first place the brain is greatly developed, reaching its climax in the apes and man. Consequent on the growth of the brain is the acquisition of intelligence with the complex behaviour which that implies.

Secondly the tendency to care for the young is more strongly developed. The offspring are nourished inside the female's body so that they are in an advanced state of development when they are born. Further provision is made for them by the capacity of the mothers to feed them on milk.

Both these devices increase the offspring's chance of survival as compared with young birds, for during the most critical stages of their lives they are independent of their parents' ability to find them special food—a factor often dependent on the weather. The degree of parental protection usually provided after the suckling period is over further reduces the mortality rate. Among the reptiles and amphibians where the young are left to hatch and fend for themselves the death rate is very high.

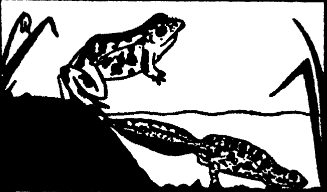
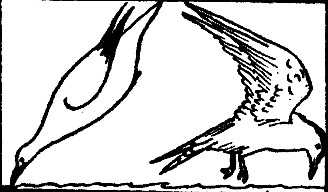
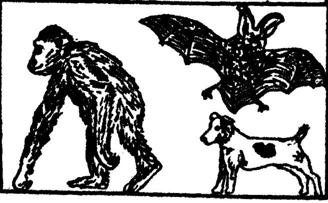
FISHES		COLD BLOODED NO LEGS - FINS ONLY GILL BREATHERS LAY EGGS IN WATER BRAIN SMALL
AMPHIBIANS		COLD BLOODED FOUR LIMBS GILL THEN LUNG BREATHERS LAY EGGS IN WATER BRAIN SMALL
REPTILES		COLD BLOODED TYPICALLY FOUR LIMBS LUNG BREATHERS LAY EGGS ON LAND HAVE SCALES BRAIN SMALL
BIRDS		WARM BLOODED TWO LEGS: TWO WINGS LUNG BREATHERS LAY EGGS ON LAND HAVE FEATHERS BRAIN LARGE
MAMMALS		WARM BLOODED TYPICALLY FOUR LEGS LUNG BREATHERS RETAIN EGGS IN THE BODY HAVE HAIR SUCKLE YOUNG BRAIN LARGE

FIG. 15.—The chief characters of the five groups of backboned animals.

This habit of the birds and mammals of caring for their young carries two other biological advantages:

(1) It generates a feeling of kinship which makes possible a prolonged family or herd life.

(2) It automatically opens up the possibility that the offspring can learn useful patterns of behaviour from their parents.

Certain birds and mammals have made good use of both advantages. But as we shall see later the creature which owes most to them is man.

Except for being warm-blooded, mammals are fundamentally different from birds in structure and behaviour. Anatomically they are easier to relate to the reptiles as a group.

On the general evolutionary principle that complex organisms have arisen from simple ones, the facts given in this brief sketch of the animal kingdom suggest the probable sequence of events shown in Table 2.

It would be logical to suppose that at one time there were just simple one-celled creatures like *Amœba*, and that from these rose the multicelled organisms which form the great invertebrate groups. We have seen no evidence that any of these groups are related in such a way as to form a sequence—one arising from another—so we represent them as separate lines branching from the original stock.

We show the fishes as arising from some invertebrate group, the amphibians arising from the fishes and reptiles from the amphibians. Birds and mammals are shown as springing separately from the reptiles.

What about the vegetable kingdom? Does a study of living plants support the theory of evolution?

Yes. It suggests that plants too have arisen as definite branches of a family tree.

There are thousands of species of one-celled plants which are almost as simple in structure as the *Amœba*. Fig. 16 shows one of them—*Chlamydomonas*, a minute organism living in pond water. The long name, which means " with a single cloak ", refers to the thick cell wall.

Although the organism swims about by means of the whip-like threads it is classed as a plant for two reasons:

(1) Its cell wall is made of cellulose, a substance which makes up the bulk of plant tissues and is never found in animals.

(2) It contains the remarkable green pigment known as *chlorophyll.* It is the possession of this substance which enables green plants to absorb the energy of sunlight and use it to manufacture sugars, starch and other foods from simple chemicals extracted from the soil and air. No animal can do this.

Because *Chlamydomonas* and its relatives are so like one-celled animals in other respects they are classed with them as Protozoa. This suggests a common aquatic origin way back in time for both the plant and animal kingdoms. It also suggests that the split into the two divergent branches came early in the earth's history. Only an early split with consequent development along quite separate lines would account for the fundamental differences between the two great kingdoms.

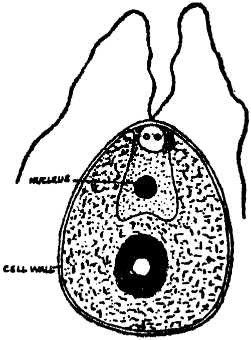


FIG. 16.—A one-celled plant —*Chlamydomonas*—which swims like an animal.

The next step in the evolution of plants seems to have been the same as that adopted by the animals—the development of the multicellular condition.

Fig. 17 (A) shows a simple plant which is little more than a cluster of *Chlamydomonas*-like cells embedded in a jelly. This organism belongs to the simplest group of plants, known as the *algas,* which includes all the seaweeds and many fresh-water plants.

A more important form of the simple multicellular condition is the " filament "—a thread of cells each fundamentally like a single *Chlamydomonas* but lacking mobility and cylindrical in shape (Fig. 17 (B)).

The filament is the basic unit of all the large algas. Even the biggest seaweeds—and some are 600 feet long—are little more than a mass of interwoven filaments showing hardly any of the specialisations of the tissue into stem, root and leaf, typical of land plants.

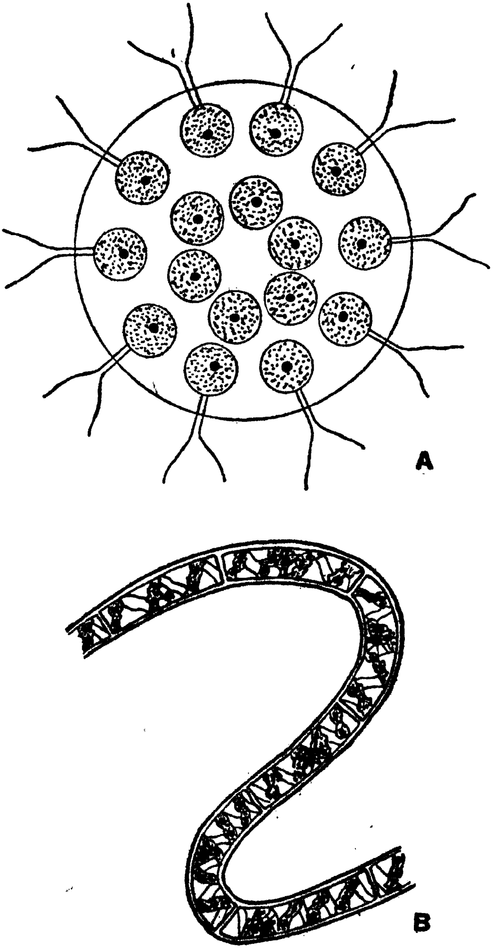


FIG. 17.—Simple algas. (A) A colony of one-celled plants, (B) a many-celled filament.

Table 3 shows the remaining group of plants in the order which their structure would suggest they have developed. (The fungi—made up of the moulds, yeasts and toadstools—form a rogue group which seems to have arisen from the algas. Having lost their chlorophyll they are forced to feed on the living tissues or on the dead remains of other plants.)

Within each of these main groups the species can be classified on the basis of obvious similarities into various subgroups and genera. In many cases these fall into natural series which cannot be logically explained except on evolutionary principles.

Does the evidence of the fossils support these tentative family trees?

It not only supports them but enables us to elaborate them·

Table 4 shows the tree of animal evolution which is suggested by a study of the fossils alone. Because the invertebrate groups seem to have separated off so early it looks more like a pollarded willow than an ordinary tree. The numbers in the vertical column correspond to the geological periods named in Table 1.

Too many link fossils are still missing for us to know exactly where the different groups spring from the main stem. But considering how young the study of fossils is and what little chance there is of finding the main links, assuming that they have been fossilised somewhere in the world, our knowledge is astonishingly full.

No fossils of animals have been found in the Archæozoic (No. 1) rocks which are exposed and have been examined at many places in North America, Europe, China and Australia. It seems therefore that animal life of a type complex enough to be fossilised in a recognisable way did not exist then. But the complexity of the fossil organisms in rocks just above in the geological time-scale suggests that the seas in which the Archæozoic rocks were laid down teemed with animals too soft to be preserved. There were apparently plants alive at the time too, for traces of graphite—a form of carbon derived from plants—have been found in rocks of the Archæozoic period.

In the Precambrian period (No. 2) Protozoans and sponges were abundant. Corals and worms—detected by their burrows in the rock—were also present. And no doubt there were many other creatures too soft to be fossilised just as today there are jellyfish, molluscs and worms which will probably leave no record of their existence in the rocks at present being laid down beneath the sea.

The most abundant fossils in the Cambrian rocks (No. 3) —large areas of which are exposed in Wales—are called trilobites (Fig. 18). These are related to crustaceans and of all well-known living things they most resembled woodlice, being, like them, able to roll themselves into a ball. But most of the trilobites were bigger than woodlice —about one and a half inches long on the average and reaching two feet in some cases. They probably crept about the sea bottom feeding on worms and other soft-bodied creatures.

Also common in the Cambrian rocks are strange creatures called lamp-shells which look like molluscs but are very different internally and are classed separately. There are comparatively few species of lamp-shells alive today but some of them are still very numerous in the warmer seas.

True molluscs were there as well in the shape of snails, clams, squids and cuttlefish. There were also a few starfishes and sea-cucumbers.

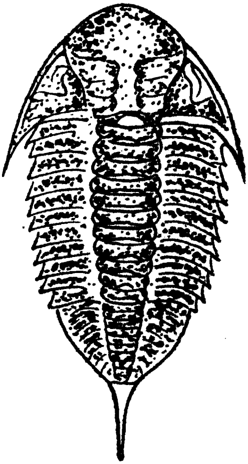


FIG. 18.—A trilobite—an early relative of the crab.

It will be seen from Table 4 that with the exception of the trilobites representatives of all the groups of animals so far mentioned have persisted until the present day. This does not mean, however, that they have not changed. On the contrary corals, molluscs, crustaceans and other creatures found in the rocks of the Cambrian period are for the most part non-existent today. They apparently gave rise to other species and then became extinct. Their modern descendants represent the top twigs of the branches which in Table 4 are shown straight and undivided for the sake of simplicity.

There are, however, some exceptional creatures which have persisted practically unchanged since Cambrian times. The lamp-shell *Lingula* shown in Fig. 19 is the most remarkable instance. It is still abundant off Japan.

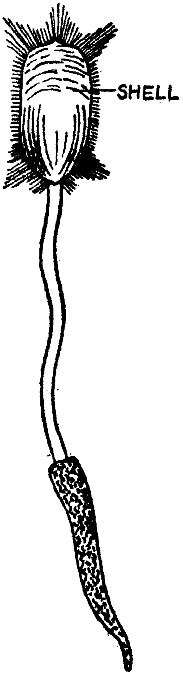


FIG. 19.—The lamp-shell—*Lingula*—which is still abundant and has remained virtually unchanged in form for about 400 million years. With its long stalk the animal burrows in mud.

The main groups of animals mentioned so far increased in numbers and types during the next period, No. 4, the Ordovician, throughout which the climate seems to have been generally mild. The trilobites in particular multiplied and spread, reaching their peak in this age. The extent of their supremacy is probably exaggerated by the geological record because, by virtue of their hard armour, they were more readily fossilised than other contemporary animal forms. But there seems to be no doubt that they were the dominant animals about 400,000,000 years ago.

The expansion of the trilobites was not, however, the most significant evolutionary development of the Ordovician age. Much more important was the emergence of the earliest back-boned animals—the first fishes. They were small armoured creatures like the form shown in Fig. 20.

It is important to bear in mind the fact that all the animals and plants so far mentioned were aquatic. It seems fairly certain—for reasons which will be given later—that all the early organisms arose in the sea. From there they soon colonised the rivers and lakes and it seems likely that the first fishes arose in fresh water, for the sedimentary rocks in which their remains are found appear to have been laid down there.

The land at this time was quite bare of vegetation or animal life, and as far as we can see from the fossil evidence no marine animals had learned to fly.

The early fishes appear to have been the ancestors of all the other backboned animals including ourselves. But first of all they gave rise to other types of fishes which colonised the seas in the next great geological periods—the Silurian (No. 5) and Devonian (No. 6). At the same time there were important developments among the invertebrates. Corals were increasing and new creatures arose like the horseshoe crabs (Fig. 21) which have persisted unchanged down to present times.

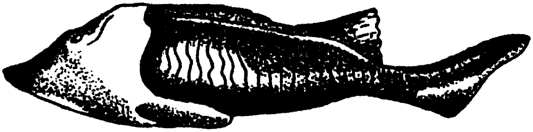


FIG. 20.—An armoured fish—one of the earliest backboned animals.

The warm Silurian period lasted about 30,000,000 years, but at its close there were still no animals on the land save for a few small backboneless creatures called millipedes.

The Devonian period was completely dominated by the fishes. Thousands of species arose including the lung fishes, which apparently were the first animals capable of breathing air and, as we have seen, have direct descendants alive today.

Whilst the fishes increased, the trilobites declined. But as they were fading as a great group many new trilobite species arose with the most elaborate spiny armour. As we shall see later this strange

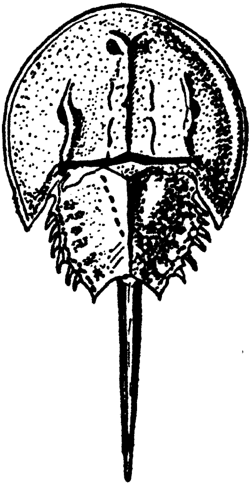


FIG. 21.—A horseshoe crab—another marine creature which has remained practically unchanged for many millions of years.

development has often preceded the extinction of a great animal group.

It was probably from a lung-breathing fish that the earliest land vertebrates—the first amphibia—arose. They were apparently preceded on the land only by a few species of millipedes and wingless insects.

Whatever the precise mode of origin of the amphibia they appear for the first time in the late Devonian rocks. The transition almost certainly took place in fresh water, for no amphibian alive today can tolerate sea water and the location of amphibian fossils suggests this limitation has probably always applied to the group.

Throughout all this time the plant life of the sea appears to have undergone but little change. Indeed to this day the seaweeds and other algas are probably much as they were in Devonian times. But before the amphibia emerged plants began to colonise the land.

The clothing of the earth's bleak surface with vegetation probably began in early or middle Silurian (No. 5) times, for fossils of plants which were well adapted to aerial life have been found in late Silurian and early Devonian rocks.

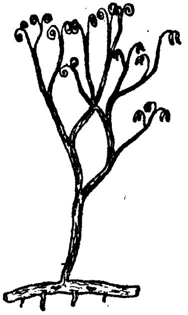


FIG. 22.—One of the earliest known land plants reconstructed from fossil remains.

Fig. 22 shows what the earliest known land plants looked like. It is not difficult to imagine such a simple structure arising from some seaweed or possibly from a fresh-water alga.

The algas may have colonised the land after a long period in which they became adapted to living in the semi-dry conditions between the tide marks, or they may have been thrust directly into the air by the gradual elevation of the sea-bed or lake bottom on which they were living. To support their weight without the buoying-up effect of water they would have to develop the woody skeletons typical of modern land plants. The fossil record shows that this soon happened, but many of the big plants which clothed the earth in early times seem to have been so soft and pulpy that they must have depended on the mutual support they got by growing in dense profusion.

By the end of the Devonian era the land plants had made great progress. There were giant club-mosses, horsetails and ferns (Fig. 23). During the next 60,000,000 years or so which made up the Carboniferous period with its warm wet climate these evergreens spread rapidly forming the jungle swamps in which the amphibians held total sway.

What did these first land animals look like ? We have a fair idea because many of their skulls, bones and footprints have been found in upper Devonian rocks in Greenland and Canada.

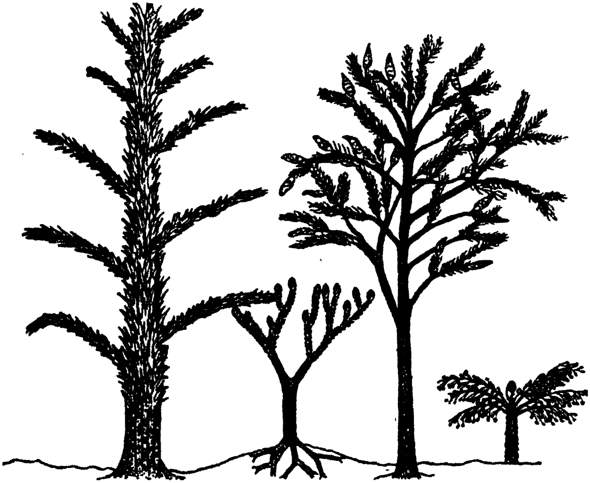


FIG. 23.—Reconstructions of the sort of trees which made up the forests of Carboniferous times and rotted away to form coal.

The earliest ones were comparatively small but they soon gave rise to species which were very large compared with living amphibians, being as big as crocodiles and not unlike them in appearance (Fig. 24). They had large flat heads with jaws armed with many rows of powerful teeth. The neck was short, and the body squat, ending in a largish tail. Their movement over land must have been awkward, for their web-footed legs stuck out horizontally from the body with the elbow and knee joints forming a right angle as shown in Fig. 25.

Apparently the skin was not provided with scales, which, as we shall see, characterised the fossil reptiles.

The large species probably fed on fish whilst the smaller ones, many of which were no bigger than modern frogs and newts, may have captured the insects which the fossil record tells us had emerged as a big group by mid-Carboniferous times. (Some of these primitive insects were relatively large. One of them—a dragon-fly—had a wing span of more than two feet.)

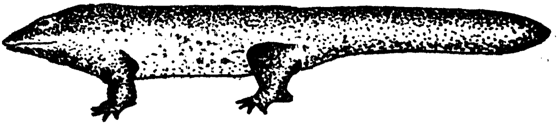


FIG. 24.—An early amphibian (*Diplovertebron*) which was as big as a crocodile.

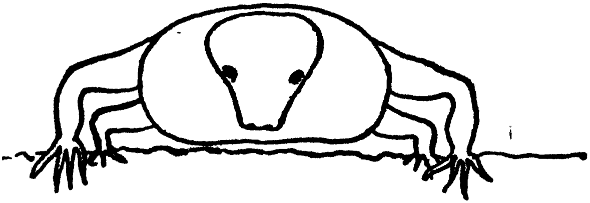


FIG. 25.—Diagrammatic head-on view of an early amphibian showing how the limbs stuck out from the body.

The geological evidence makes it quite clear that for about the first 40,000,000 years of the Carboniferous period the amphibians were the highest forms of life the earth had ever seen. Their success is shown by the world-wide distribution of their fossil remains. But during the next 20,000,000 or so years for which, we believe, the Carboniferous period lasted, a new type of animal arose more advanced than anything which had gone before—the first reptile.

We have seen that the most important advantage living reptiles have over the amphibia is their independence of the water. The early reptiles seem to have had this advantage too and soon spread over dry parts of the country from which the amphibians were excluded. They were preceded in this pioneer colonisation by vegetation in the form of seed-bearing plants called cycads and were quickly followed by the first true conifers.

The skeletons of the early reptiles were very like those of certain small amphibians living in middle Carboniferous times and there can be little doubt that the new group sprang from this or from a similar amphibian offshoot. The change-over was tremendously important, for the descendants of these first reptiles were destined to oust the amphibians as the dominant animal group and to lord it over the earth, sea and sky for something like 150,000,000 years.

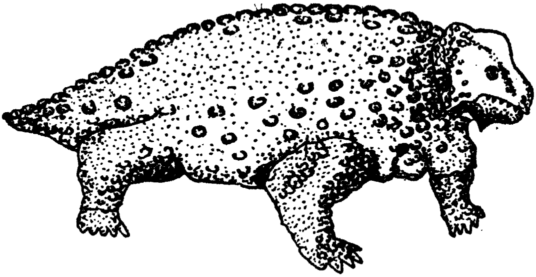


FIG. 26—Reconstruction of *Scutosaurus*—one of the earliest known reptiles—from fossil remains found in Europe.

Whilst the reptiles were emerging the trilobites were declining still further and they died out altogether during the next period, the Permian (No. 8), which lasted about 30,000,000 years.

Fig. 26 shows what one of the earliest known reptiles must have looked like according to reconstructions of the fossilised bones. Known as *Scutosaurus*, it inhabited Europe during Permian times. It was a massive creature about nine feet long and apparently dragged its body along the ground. It seems that the elbows and knees were a little more tucked in towards the body than was the case with the amphibians, but the animal was still a slow mover and was probably entirely herbivorous, feeding chiefly on roots, for its limbs were obviously adapted for digging.

Severe climatic changes marked the end of the Carboniferous period (No. 7). Cold winds began to blow through the subtropical cycad forests. The swamplands gradually froze. Violent movements of the earth culminating in the formation of great volcanoes and other mountains took place in Permian times. The ice gradually relaxed its grip but the general climate fluctuated considerably. It was a severe testing time for animals.

By the end of the following period—the Triassic (No. 9)—the once-mighty amphibians were reduced to the insignificance in which they remain to this day. The reptiles on the other hand multiplied both in numbers and species, filling the niches left by the dying amphibians and exploring new environments. Though essentially land animals, they also exploited the rivers and lakes as hunting grounds and successfully invaded the sea, which the amphibians had never been able to do. Some even developed wings and broke the monopoly of the air held by the insects.

Though the Triassic period was relatively short—about 25,000,000 years—it was tremendously important, for it saw the rise of the first mammals, the dominant group of modern times. We have seen that a most important difference between mammals and reptiles is that the former are warm-blooded and therefore better able to withstand cold. But in the warm climate which characterised the Triassic age this was no immediate advantage. The mammals had arrived but for many millions of years they were destined to remain tiny insignificant creatures skulking in the undergrowth feeding on insects and fruits. For the reptiles the golden age was only just beginning.

It was above all the age of the *dinosaurs*—a reptilian stock which for size, numbers and diversity of form and habit have never been equalled. The dinosaurs were far in advance of any reptiles alive today. For whilst crocodiles, for instance, have to rest the weight of their bodies on the ground after every few steps some of the dinosaurs were as mobile and fleet of foot as modern mammals. Moreover many of them had highly prehensile hands.

Fossil remains of dinosaurs have been found throughout the world. They ranged from creatures little more than a foot long when fully grown to creatures at least 80 feet in length and weighing more than 40 tons.

Fig. 27 shows a reconstruction of the biggest dinosaur yet discovered—the famous *Diplodocus*. Like nearly all the giants in the animal world it was a vegetarian and that it spent most of its time in water—probably on the sea-shore—is suggested by the fact that its nostrils were located on the top of its head. Partly immersed it would have less difficulty in supporting its mighty weight and would find it easier to escape the ferocious carnivores which preyed on it. These too were dinosaurs. In the terrible *Tyrannosaurus*, which needed a body nearly 50 feet long to support its massive jaws, carnivorous dinosaurs reached the peak of frightfulness. Not

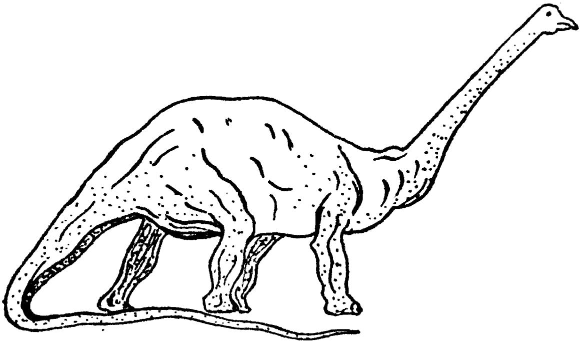


FIG. 27.—*Diplodocus*—the biggest known land animal. It weighed more than 40 tons.

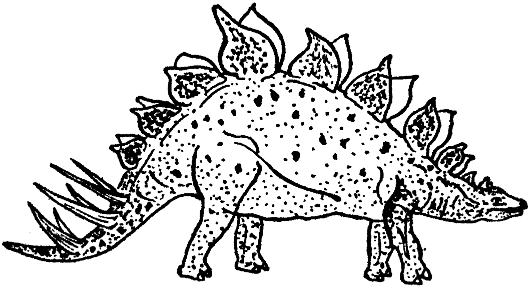


FIG. 28.—*Stegosaurus*—an armoured dinosaur about 25 feet long which lived in America.

even the formidable armour plates developed by some of the other dinosaurs like *Stegosaurus* (Fig. 28) were proof against them.

In addition to these fabulous creatures a number of reptiles arose which though comparatively insignificant were destined to outlast their giant contemporaries. These were the ancestors of the modern tortoises, lizards and snakes.

Evidence of another evolutionary experiment on a smaller scale are the fossil remains of flying reptiles—best known of which are the pterodactyls. To begin with these nightmarish creatures were of small size, most of them being no bigger than sparrows, but later giant forms arose with a wing span of up to 20 feet.

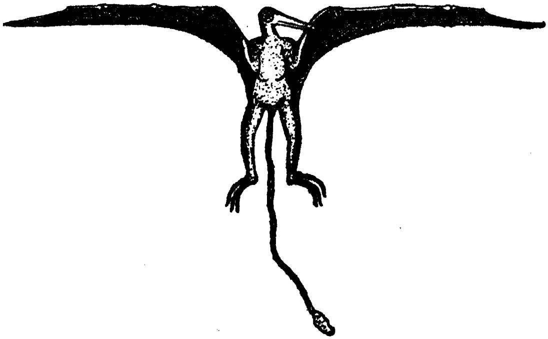


FIG. 29.—A long-tailed flying reptile which lived in Jurassic times. It had a wing span of about 2 feet.

Fig. 29 pictures one of these flying reptiles, called *Rhamphorhynchus*. It was generally like a bird in structure but its wings were made up of folds of skin instead of feathers and it had teeth and a long bony tail.

No descendants of the flying reptiles have survived. The birds did not arise from the pterodactyls. This is made clear by the fact that they occur in rocks of the Jurassic (No. 10) period only slightly younger than those containing the first pterodactyl remains. It seems that the two groups sprang almost simultaneously from separate, though nearly related, reptilian stocks and pursued independent lives of development.

The final results—the pterodactyl on one hand, the bird on the other—are superficially alike because they solved the problem of flight in broadly similar ways. But such superficial resemblance is no evidence of close relationship. When it occurs between two groups which from other evidence have clearly developed separately, then it is said to be the result of *parallel evolution* or *convergence*. The similar shapes of the whale and the fish form another example.

Anatomical investigation quickly shows up real differences in convergent resemblances. The pterodactyl wing, for instance, was quite differently constructed from the wing of a bird, being simply a huge fold of skin supported by the much elongated little finger.

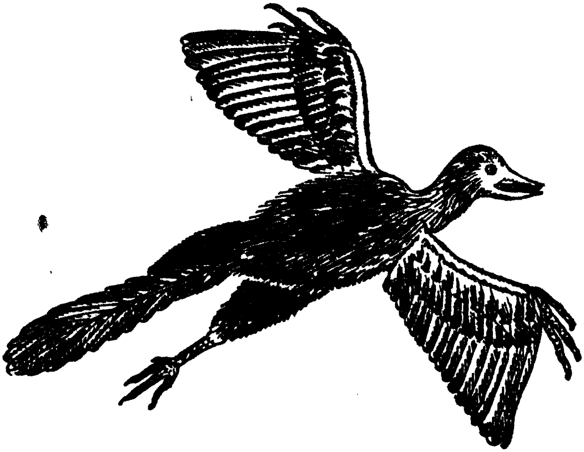


FIG. 30.—The oldest known fossil bird—*Archæopteryx*. About the size of a crow, it had teeth, a jointed bony tail and claws on its wings.

Fig. 30 shows a reconstruction of the earliest known bird, *Archæopteryx*, from the fossil remains pictured in Fig. 2. It was about the size of a crow and like the first pterodactyls it had teeth and a long bony tail, which are not present in modern birds. But it also had feathers which are not present in any reptile, though they could be and probably were derived from reptilian scales. These feathers were more efficient conservers of warmth than scales or armour and the odds are that *Archæopteryx* was warm-blooded like all modern birds. It seems likely, however, that *Archæopteryx* was by no means so efficient a flier as the contemporary pterodactyls. It probably used its wings only for gliding down from tall trees. Powerful claws on the wings made it a good climber. Wing-claws were lost as birds developed the power of sustained flight and, because of their more efficient physiology, rapidly outstripped the pterodactyls in aerial performance.

These early birds were also an advance on the pterodactyls in that their legs were strongly developed and more suitable for perching.

The Jurassic period (No. 10), which lasted for about 25,000,000 years, was a great age of successful experiment in the animal world. It was then that the bony fishes—the highest and most successful of the fish groups began to spread following their origin in the Triassic. It was also a period of spread for the small mammals which probably first appeared in South Africa. By the middle of the Jurassic period small mammals were certainly living as far afield as China and America.

The Jurassic was succeeded by a 65,000,000-year warm period called the Cretaceous, at the end of which came changes which entirely altered the fauna and flora of the world. The giant reptiles died out completely, leaving no direct descendants. With the end of the reptilian dynasty the mammals and birds found themselves without serious competitors. For reasons which will be fully discussed later they were able to survive whilst the more formidable but more specialised dinosaurs succumbed. They increased rapidly in numbers and species and filling the multitude of environmental niches previously held by the reptiles they became the dominant creatures of the earth and sky. At the same time the deciduous trees and other flowering plants of modern type arose and spread at a phenomenal speed.

The geologists have not been able to explain this rapid rise to dominance of the flowering plants. Nor have they been able to tell us why the great reptiles died out so suddenly and completely. One theory suggests that the earth warmed up so much that the dinosaurs became sterile. But this cannot have been the major cause, for though the sudden onset of very warm conditions might account for the disappearance of the reptiles from the land it could hardly explain the same phenomenon in the sea which buffers its inhabitants against the effects of severe temperature changes. And giant ocean-living reptiles which were common at the beginning of the Cretaceous period went with their terrestrial relatives into extinction at the end. Known as mosasaurs, ichthyosaurs and plesiosaurs, they were ferocious fish-eaters as much at home in the sea as are the whales of today and giving birth to living young instead of laying eggs like other reptiles. (In the Natural History Museum, London, there is a fossil female ichthyosaur containing the skeletons of six unborn young.)

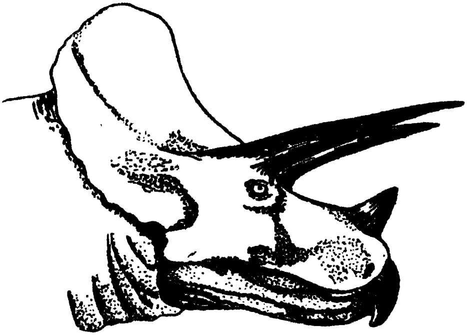


FIG. 31.—One of the last of the dinosaurs—*Triceratops*—a three-horned monster like a rhinoceros.

The same objection also applies to blaming competition from the mammals for the snuffing out of the reptiles.

If, however, it ever had come to a show-down between the two groups ultimate victory for the mammals was inevitable, for the reptiles were sadly lacking in brain size and hence in ingenuity. Thus the brain of the *Diplodocus* as reckoned from the volume of the cranium was no bigger than a hen's egg: the elephant—the only living mammal of comparable size—has a brain fifty times larger. It may be that the gross disproportion between body and brain was the underlying cause of the end of the great reptiles, especially in view of the fact that some of the smaller ones survived.

The general biological absurdity of the big reptiles was even further intensified during the mild Cretaceous period by the development of species with excessively large skulls armed with huge spines. The well-known *Triceratops* (Fig. 31), a herbivorous giant with a great, bony shield growing backwards from the skull, was typical.

Among the fossils there are mammal-like reptiles and reptile-like mammals and somewhere between the two must have originated the first true mammals—the first animals to suckle their young. That a gradual change-over from the egg-laying habits of reptiles to the body-incubating and suckling habits of mammals is possible is strongly suggested by a study of what appear to be the most ancient surviving mammals—the duck-billed platypus and the spiny ant-eater.

The duck-billed platypus is an aquatic mole-like creature, native to Tasmania and south-eastern Australia, with a flat bill which enables it to hunt in mud. It qualifies as a mammal since it suckles its young, is warm-blooded and has the typical mammalian four-chambered heart. The females have no teats, however—the milk being exuded on to the fur and licked off by the young—and they lay large, yolky, shell-covered eggs.

The hedgehog-like spiny ant-eater or echidna, again of Australia and Tasmania, also lays eggs, which the female places in a pouch where they complete their development.

The further step towards complete internal incubation is provided by the kangaroos and other pouch-bearers. Female kangaroos do not lay eggs but their young are born after less than six weeks' gestation, by which time they have undergone little development. The newly born kangaroo is only about one inch long and it has to complete many more weeks of growth and differentiation in the mother's pouch, where it is force-fed on milk, before it can be said to be fully developed.

Though it is clear from their anatomical peculiarities and their geographical restriction to Australasia that the duck-billed platypus and the echidna are remnants of an extremely ancient stock, very little is known for certain about their ancestry because of lack of fossil evidence. Recent excavations in England and China have proved, however, that in Triassic times there were certain reptiles, called ictidosaurs, which had many structural resemblances to the platypus.

It may well be that the platypus does not represent a direct link between reptiles and the main mammal strain but is a descendant of a dead-end offshoot of the early mammal stock. Perhaps the reptiles which gave rise to the main mammalian line were already fully viviparous, as we know many of the dinosaurs were. The likelihood of ever deciding such a point is made more remote by the fact that such features as milk glands, pouches and internal reproductive organs are not preserved in the fossils.

It is fortunate that as regards broader issues bones do reveal a great deal about the form and evolutionary position of the animals to which they belong. The trained zoologist can readily distinguish between a mammalian and reptilian skull, for example. The mammalian skull is more compact and is made up of fewer separate bones. Reptiles have a single bony knob at the base of the skull to articulate the head with the backbone: mammals have two such knobs. In reptiles the lower jaw is made up of several bones: in mammals there is a single jawbone. Whilst mammals have a chain of three bones in the middle ear, reptiles have only one bone.

Most reptiles have many teeth which are all rather similar and can be renewed whenever they wear out: most mammals have only a few teeth of markedly different kinds—incisors, canines, molars and premolars—and which can be renewed once only.

In this way rat-sized creatures which lived in Jurassic times have been definitely identified as mammals, whilst a dog-like creature called *Cynognathus* of earlier—Triassic—date has been established as clearly a reptile. *Cynognathus* had mammal-like teeth and a double articulation of the skull and backbone. It apparently walked like a mammal with its body well off the ground and its legs tucked in close to its trunk. But it was still essentially a reptile as regards the basic structure of its skull and bones and may well have been in the direct line of descent between reptiles and the main mammalian stock.

The great expansion of the mammals as a group did not begin until the Eocene period (No. 12) which followed the Cretaceous. It was at the beginning of this generally warm period that the first grasses appeared. By the middle of it there were many species of grazing mammals wandering in huge herds over the new plains in addition to the multitude of pouch-bearers—the marsupials like wombats and kangaroos—and insect-eaters which had emerged in the Cretaceous age.

Warm-bloodedness probably enabled them to extend the range of vertebrate distribution both north and south. The definite value of warm-bloodedness in this respect is shown by the geographical distribution of animals today. There is a great abundance of cold-blooded creatures in the tropics but they peter out in the temperate regions. Warm-blooded animals on the other hand have a world-wide distribution.

The skulls of the early mammals show that they had brains not much bigger than those of the great reptiles but the brain size of their descendants rapidly increased. With it came the urge for communal life—the herd instinct—with its great survival value.

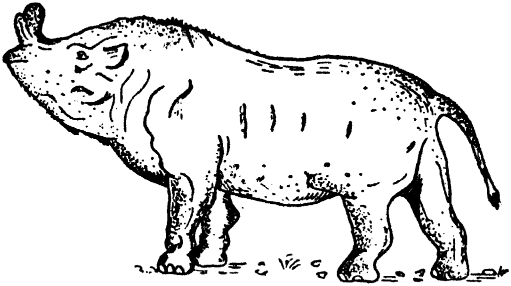


FIG. 32.—*Brontotherium*—an experimental mammal bigger than a hippopotamus which became extinct in Oligocene times.

Among fossils of early mammals which have been found in rocks of the Eocene period are the immediate ancestors of horses, camels, pigs, whales, monkeys and many experimental species like the Titanotheres (Fig. 32) which died out in the cooler Oligocene period (No. 13) leaving no descendants. In rocks of that relatively short (10,000,000-year) time remains of the first carnivorous mammals—wolves and cats—are also found.

The birds also expanded rapidly and in addition to flightless species like giant ostriches, which have since become extinct, representatives of most of the main groups of birds we know today such as eagles, gulls and owls, were in existence by the end of the Eocene period. There were also some huge flying birds—the African *Gigantornis*, for example, which had a wing span of at least 20 feet.

Apes emerged during the next period—the Miocene (No. 14)—apparently originating in Central Africa but quickly spreading to Asia and Europe. Throughout this and the next age—the Pliocene—the mammals increased their hold on the land. Their abundance throughout the world at that time seems to have been on the scale of their numbers in Africa when the white man first went there.

Then with the onset of icy conditions at the end of the Pliocene and the beginning of the next period—the Pleistocene (No. 16)—the mammals suffered a reverse on the scale of that which overtook the reptiles at the end of the Cretaceous. Millions perished in a relatively short time. Evidence of this calamity is rich in Britain. In the area round Wookey Hole, Somerset, for instance, the remains of mammoths, early rhinos, reindeers, bison, cave lions, bears and hyenas lie in profusion. No doubt the coming of the ice was responsible for many deaths but the main cause of the great extermination is unknown.

It was not until the Pleistocene period about 1,000,000 years ago that man-like apes and later early men, from which we are undoubtedly descended, first appeared.

What other evidence is there of man's evolutionary relationship with animals?

The general make-up and mode of action of the human body are basically similar to those of all other backboned animals from the amphibians upwards. The skeleton, digestive organs, nervous system, eyes, blood system, reproductive organs, etc. are constructed and work in the same general way as those of lower vertebrates. In fact so similar are man's anatomy and physiology to those of an animal as low down in the evolutionary scale as a frog that a study of such a species is considered as an essential part of a doctor's early training.

To illustrate this general similarity Fig. 33 compares the digestive systems of a frog and a man. Not only are they fundamentally alike in structure but the intricate details of

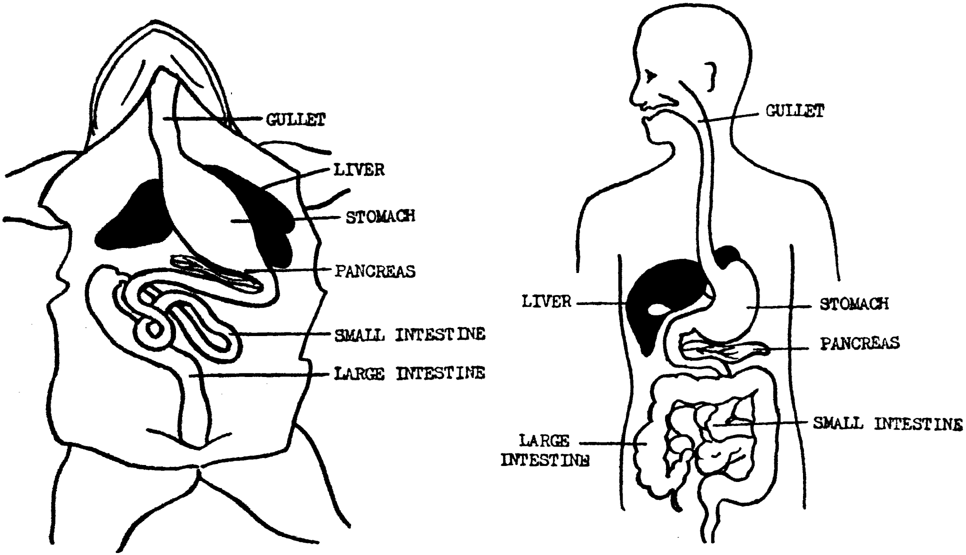


FIG. 33.—The digestive systems of a frog and a man compared.

their working closely correspond. The same digestive ferments are found in the same places in both animals and the ways these function are almost identical.

This anatomical and physiological relationship is much closer when man is compared with another mammal—a nearer relative—even when this is as different in external form and habit as a dog. The gross similarity between man and a gorilla is too obvious to need elaboration. Comparison of the internal structures shows that the likeness is not merely superficial. The ape even has the organs of speech though inferior brain development prevents their use. There is no doubt, in fact, that in many structural respects the gorilla is closer to man than it is to the chimpanzee.

The presence in the human body of certain structures which serve no purpose but are of definite use to lower mammals in which they also occur is further evidence of man's animal ancestry. Our ear muscles provide a good example of such *vestigial* organs.

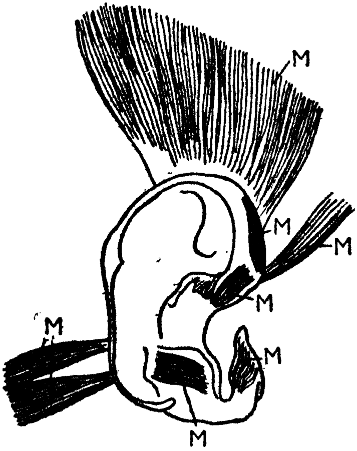


FIG. 34.—The useless muscles of the human ear.

Most mammals can move their ears and they make full use of this power to improve their judgment of the direction from which a sound is reaching them. As Fig. 34 shows, the same muscles are present in the human body but few people can use them to move their ears and to those that can the ability has no more than a party-trick value. How can the presence of these muscles be explained except on the basis that the ywere once useful and have since degenerated ?

The appendix which is quite useless in man is larger and serves some digestive purpose in lower herbivorous animals. The little red fold of skin in the corner of the human eye is bigger and movable in many mammals, serving as an additional eyelid.

The closeness of man's ties with the animals is brought into even finer focus by a study of his *embryology*—the stage of his development from the moment of conception to birth.

Like all other vertebrates he begins life as a single-celled egg little different in gross appearance from an *Amœba.* Then he becomes multicellular and gradually develops a simple backbone. At one stage he has a definite tail and though he never breathes by means of gills he develops the rudiments of gill-arches—features associated with gill breathing and serving no other purpose.

It has been widely held that in going through these different stages, corresponding so closely as they do with the evolutionary stages shown by the fossils, every man "climbs his own genealogical tree". This interesting theory has doubtless been over-elaborated but basically it must be true. How else can the undoubted presence of gill arches in the human embryo be explained except as evidence of an aquatic ancestry?

Many people though admitting the weight of all the evidence and having no comparably reasonable theory to offer still find it impossible to believe that a creature as intricate in structure and complex in behaviour as a man can really have arisen by evolution from an organism like an *Amœba.* Yet they cannot deny their own individual development from a one-celled and seemingly featureless egg.

To the biologist knowing the details the fact that all this takes place within nine months is far more difficult to comprehend than the idea that something similar happened to man as a species in the course of 2,000 million years.

What are considered to be the most important steps in evolution from the invertebrate stage to man?

(1) The development of a bony backbone and skeleton without which large animals could not live out of water.

(2) The acquisition of lungs, making air-breathing possible.

(3) The development of hard-shelled eggs, severing the final compulsory tie to an aquatic life.

(4) The origin of warm-bloodedness, giving reasonable independence of the weather.

(5) The retention of the eggs within the body, providing better protection and giving further independence of climate. (The eggs of reptiles are, for the most part, hatched out by the heat of the sun.)

(6) The development of the habit of parental care, opening up the possibility of family life and the instruction of the offspring.

(7) The growth of the brain, making thought possible.

(8) The development of the prehensile hand.

(9) The development of the power of speech, allowing the communication of thought.

Is it amply proved that man is descended from an ape-like stock?

There is no other way of interpreting the ever-increasing evidence provided by fossils.

There are five important differences between modern apes and modern men:

(1) The size of the brain is much bigger in men—about 1,400 cubic centimetres in the average male European compared with 600 c.c. in the male gorilla, which has the biggest brain among the apes.

(2) The shape of the skull is different. In man the top of the skull is domed to accommodate the big brain, whereas in apes the forehead slopes backwards at a sharp angle (Fig. 35). The ridges above the eyebrows are very prominent in the apes. Man is characterised by a definite chin—a feature entirely missing in the apes. The apes' jaws are relatively much bigger and pushed forwards.

(3) Man walks in a more erect position with the hands always off the ground. As a result the skeleton is of a somewhat different build and the hole in the skull through which the spinal cord communicates with the brain is set at the base instead of at the rear.

(4) The teeth, though of the same number and general type, are markedly different in shape and relative size. They are much bigger in apes, the dog teeth (canines) being so large

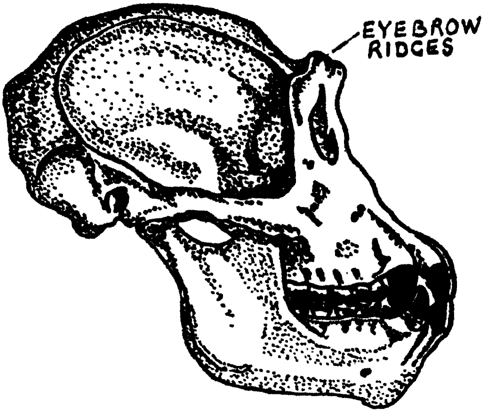


FIG. 35.—Skull of a chimpanzee.

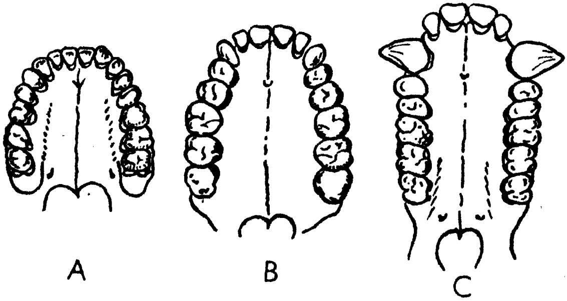


FIG. 36.—Palate of a modern man (A), a Dartian (B) and a chimpanzee (C).

that they have to interlock when the mouth is closed. The front teeth—the incisors—slope further forwards in the apes and are generally broader than in man. There are also definite gaps between the teeth immediately in front of the canines, which are not present in man (Fig. 36).

(5) Man can do far more with his hands. Apes have long arms with hands adapted to life in trees. They are excellently constructed for moving about in branches, but because the thumb is not opposable to the fingers the hands of the ape are poorly constructed for handling tools. (Apes can be taught to use simple tools but because of these anatomical limitations they can never develop much manual dexterity. It is interesting to note, incidentally, that apes never use sticks or stones as weapons.)

Now in rocks of the early Miocene (No. 14) period the remains of extinct apes have been discovered which seem to have some human features. Thus one of them, which has been called *Proconsul*, although thoroughly ape-like in most of its characters, seems to have been a ground-dweller like man. Its skull is thin-walled and some of its teeth are rather human-looking.

In rocks laid down a little more recently—in later Miocene and perhaps early Pliocene (No. 15) times—the remains of another ape which is more man-like have been found. Called *Dryopithecus*, this creature seems to have walked more upright than modern chimpanzees and its teeth were very near-human. But in other respects—brain size, skull shape, etc.—it was an ape.

From still younger rocks which seem to be definitely of the late Pliocene period a group of fossil apes with quite definite man-like characters has been unearthed in Africa. Called *Dartians*, they almost certainly walked upright and their hands may have been sufficiently near-human to enable them to use primitive weapons. Their teeth were more human than ape-like (Fig. 36); their eyebrow ridges were comparatively small and in some cases were absent altogether. Their brain—as measured by the cranium-capacity of their fossil skulls—was bigger than a gorilla's. At the same time the skull in its general proportions was rather like a chimpanzee's and the jaws were massive.

Were these Dartians apes or men then? Sir Arthur Keith, our foremost anthropologist, has suggested a reasonable answer to this question:

The most primitive living man, the adult Australian aboriginal, sometimes has a brain with a capacity as small as 855 cubic centimetres. We have seen that the biggest existing ape brain—the gorilla's—averages about 600 c.c. (it sometimes reaches 650 c.c.). Keith has therefore suggested that a brain of 750 c.c. capacity is a sound working criterion for marking the border-line between the apes and man. By this standard then the Dartians with a 650-c.c. brain would definitely be classed as apes.

So far as the known fossil record shows there were no creatures alive in Pliocene times that could properly be called men. But the rocks of the next geological period—the Pleistocene (No. 16)—tell a different story.

Excavations of some of the earliest rocks of that age have revealed that about 800,000 years ago there lived in Java chinless, ape-like creatures with a brain volume of 930 c.c., which is well above the human minimum. The teeth were human in form and the creature, which has been called *Pithecanthropus*, meaning "ape-man", must have walked erect, though not quite as vertically as modern man. It was bigger than a Dartian, which seems to have been about the size of a modern pigmy. Examination of its lairs shows that it was certainly intelligent enough to slit the long bones of animals in order to obtain the marrow.

Living at the same time in China was another race of similar but more highly developed creatures which have been called Pekin-men. A considerable number of their skulls and other fossil relics have been excavated from Pleistocene rocks and critically examined. They still had some marks of the ape—low foreheads, prominent ridges over the eyebrows and big jaws, but their brains were large, reaching a volume of more than 1,200 cubic centimetres (Figs. 37 and 38). Moreover, as excavation of their caves has shown, these creatures certainly made fires and used crude stone implements.

Then in younger rocks about 450,000 years old a toothed jawbone so man-like that zoologists have had to classify it as belonging to a species of *Homo*—true man—has been discovered in Germany. There is abundant evidence that this

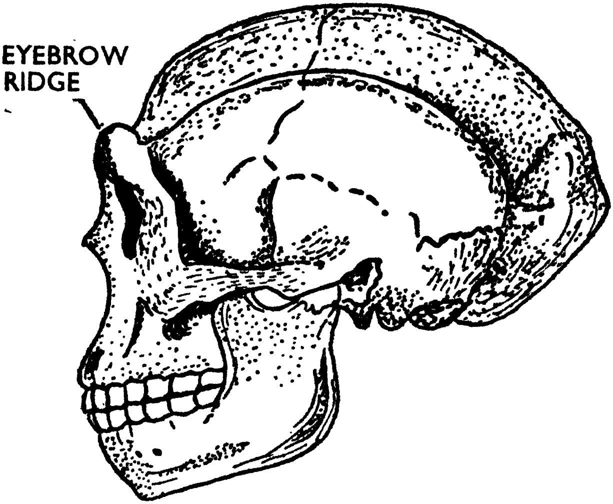


FIG. 37.—Reconstructions of the skull of a female " Pekin-man ".

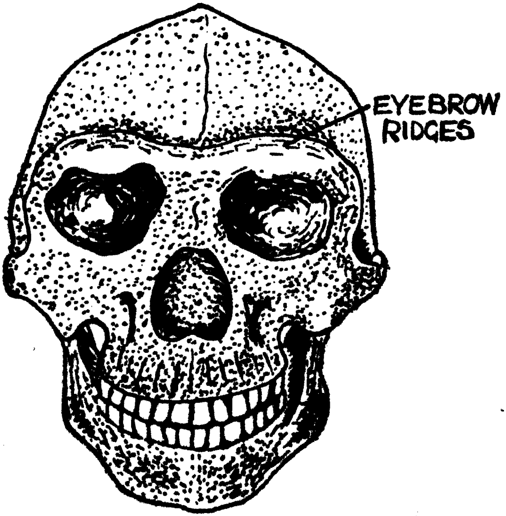


FIG. 38.—Front view of the skull shown in Fig. 37.

so-called Heidelberg man was intelligent enough to chip flints to use as implements.

True men of our own kind—the *Homo sapiens* species—seem to have lived in Australia and probably elsewhere 150,000 years ago. About 60,000 years later their descendants, known as Cromagnons, who reached Europe, were a fine race little different from us in brain capacity and appearance except that they stooped, were probably more hairy and had bigger ears and smaller chins.

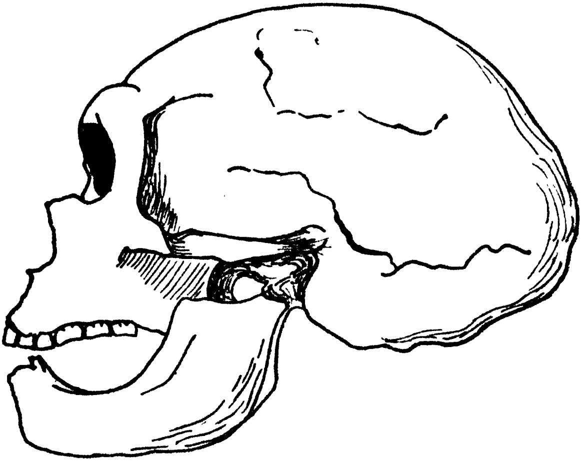


FIG. 39.—Skull of a Neanderthal man. Note the brow ridges and the size of the back of the brain-case compared with the front.

When these people arrived in Europe they found living there a type of man more primitive than themselves who has been called Neanderthal man because his remains have been discovered at Neanderthal, near Dusseldorf in Germany. Many almost complete fossil skulls and skeletons show that this creature had a chinless, ape-like face, with prominent ridges above the eyebrows and stooped as it walked on short, bowed legs (Fig. 39). Its brain was often bigger behind than ours but in the upper and front regions, which are the seat of intelligence, it was much smaller. Neanderthal man certainly made fires, probably dressed in skins and buried the dead. From the structure of the lower jaw, however, it would seem that unlike Cromagnon man, he was incapable of speech.

Recovered remains of these two contemporaries show that they lived side by side for thousands of years and may even have interbred, though this seems doubtful. Eventually, however, the Neanderthal type, though once spread over much of the world, became extinct and apparently left no direct descendants.

The later history of these early men of the " Old Stone Age " is well known from the study of their flints, pottery and implements made at such places as Wookey Hole and Cheddar Gorge. They were superseded about 12,000 years ago by men more advanced mentally who polished their stone implements and grew crops—the men of the Neolithic culture or New Stone Age. From them the descent of man through the Bronze and Iron ages to historic times is well understood.

There seems to be only one reasonable way of accounting for all these facts :

Modern man developed from some primitive ape-like stock —possibly the Dartians—which lived in Africa or some other tropical country. (Geological evidence shows that the now temperate lands were ice-bound at the time of man's emergence.) This stock arose from a division of the ape-line which probably took place way back in Miocene (No. 14) times. One branch of the division apparently gave rise to the Dartians, the other to the modern apes. It is clear that living apes and men are the end product of two separate and specialised lines of development. One line lived in trees and developed the long arms, short legs and other body characteristics which enabled them to swing from branch to branch. The other line became ground dwellers and developed the upright habit with the longer legs, shorter arms and highly prehensile hands.

There is no chance that man descended from apes as we know them. Apes are so specialised structurally that such an evolution would have been anatomically impossible.

In the course of about 1,000,000 years man has developed a bigger brain, an upright posture and still more prehensile hands.

The Java men, Pekin men and Cromagnons may represent links in a direct chain of descent. Neanderthal and Heidelberg men plus another type not previously mentioned, called Piltdown man, were "experimental" species which became extinct—a fate which we know befell some representatives of every group of animals during their long evolution.

SECTION II

INHERITANCE AND VARIATION—THE "RAW MATERIALS" OF EVOLUTION

Is there any evidence as to how the simplest organisms—the Protozoans like Amœba*—first arose?*

We know from the facts of astronomy and geology that the earth's surface was once too hot to support any form of life. We know too that all living things are built up of chemicals which separately are inanimate—substances like fats, carbohydrates (e.g. sugar), proteins and minerals. We must therefore conclude that the first living things arose from a collection of inanimate chemicals which in some manner became endowed with the special property we call "life". It is hard to imagine how such a collection of chemicals could have been brought together on dry land, but it is conceivable that it might have happened in water. And, of course, the fossil evidence shows that the earliest forms of life were aquatic.

Now there are in existence organisms which seem to be halfway between ordinary living things and inanimate chemicals. They also have the simplest structure of any known object that can truly be said to be alive. It is not unreasonable therefore to regard these *viruses*, as they are called, as a living clue to the origin of the first organisms.

Consider this example:

There is a certain disease of tomato plants called "bushy stunt" in which the leaves and stems are seriously malformed.

From the sap of infected plants scientists are able to extract minute protein crystals which are as inanimate as any other crystals, those of table salt, for instance. Thus they can be kept indefinitely in a sealed test tube without undergoing any change whatsoever.

But if these crystals are introduced into the sap of a healthy tomato plant they immediately take on the properties of living matter. Each breaks down into thousands of tiny spheres which behave as parasites feeding on the sap and multiplying rapidly. The tomato plant soon shows specific symptoms of disease as the attack spreads through its tissues. Eventually far more crystalline virus can be extracted from it than was first injected.

In such a virus then we have something which can alternate between a live and a lifeless state. It is therefore not unreasonable to suppose that the first-ever " living chemicals " were like viruses in structure.

Now no viruses—and there are many different kinds—can remain in the live state except in contact with the body fluid of some other organism. So it would seem that before the first "living chemicals" could become independent creatures they would have had to gather round themselves some nourishing fluid of their own. This could have been effected by withdrawing substances from the water—almost certainly sea-water—in which the prototype organisms apparently found themselves. One can imagine a semi-fluid jelly building up in this way round a primitive nucleus something like a virus in structure to produce a hypothetical organism not unlike an *Amœba* in appearance.

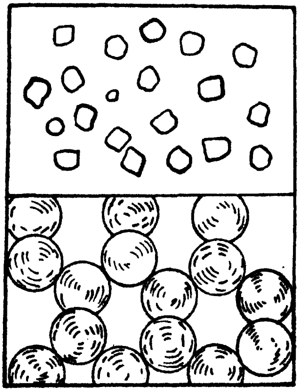


FIG. 40.—*Above :* Crystals of a virus causing a disease of turnips called yellow mosaic, magnified many thousands of times. *Below :* Part of a crystal still more highly magnified to show how it is made up of tiny spheres which separate when the crystal is dissolved.

We know that modern protoplasm is a complex mixture of proteins, carbohydrates, fats, etc., so our theory of its origin assumes that similar materials once existed free in the sea, which they certainly do not now. Such an assumption is not entirely unwarranted, for conditions in the early days of the world were very different from those of today. If, for instance, the air was then heavily charged with carbon dioxide of volcanic origin and nitrogen compounds formed in intense lightning storms, then the basic materials were available for the formation of organic substances. It has also been suggested that certain of the sun's rays now largely filtered off by the atmosphere may have played some part in energising inanimate matter.

Whatever the conditions were that made the origin of life possible they do not seem to have been repeated since earliest times. All the evidence supports the belief that all the animals and plants alive today are descended from one origin or at the most a few separate and more or less simultaneous origins.

We can picture then, this hypothetical amœboid creature living in what is usually called the primeval slime. It may possibly have gone on feeding by the absorption of organic substances synthesised in the manner suggested but it seems certain that the development of chlorophyll was an essential step to further evolution.

All existing animal life is ultimately dependent on the foods built up by green plants through the agency of chlorophyll. It would, therefore, seem likely that unicellular plants preceded the unicellular animals from which invertebrate and later vertebrate multicellular creatures arose.

We know far too little about these times 2,000,000,000 years ago to argue the point finely, but it must be remembered that any deficiencies in presenting a reasonable picture of how life arose in no way weaken the theory of evolution. This purports to explain only how life developed once it had arisen.

According to the general evidence the next evolutionary step after the origin of the one-celled organisms like Amœba *was the development of many-celled creatures like sponges and jellyfish. How could this step have been brought about?*

An *Amœba* breeds by simply dividing into two similar pieces which each eventually grow to the size of the parent. The first stage of this process, which is pictured in Fig. 41, is the division of the nucleus into similar daughter nuclei. Then the protoplasm becomes nipped across between the daughter nuclei and finally separates.

Now if instead of separating to lead an independent life the two cells so formed remained attached, a bicellular organism would result. These two cells could then divide to form four and so on, producing a multicellular creature.

Of course, the mere clinging together of a mass of amœboid cells is not enough to produce an organism as beautifully proportioned and complex as a jellyfish. Whereas the daughter cells of the *Amœba* are exactly alike, the various cells of a multicellular organism usually have a different form and work differently. We do know, however, that a single cell no bigger than an *Amœba* and similar in basic structure can give rise by simple division to a mass of cells each with quite different functions and superbly organised—for it happens every time a human being is conceived and develops.

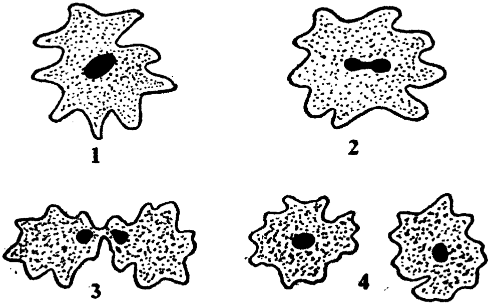


FIG. 41.—How an *Amœba* divides to form two independent organisms.

There are about 100,000,000,000,000 cells in a fully grown man and they all arise by the successive divisions of a one-celled egg which, like *Amœba,* is just a blob of protoplasm containing a nucleus and surrounded by a cell wall (Fig. 42). The first few thousand cells produced by the egg are all alike to begin with. But they gradually become *differentiated,* i.e. they alter their form and become specialised for particular purposes. For instance, some give rise to the skin, whilst others produce the digestive system; some form the brain, others the sex organs and so on.

It is, therefore, not very difficult to visualise the circumstances of that tremendous evolutionary step—the origin of the multicellular organism from the unicellular. First came cell division without separation to produce a mass of similar cells. Then came differentiation so that different parts of the organism became specialised for various purposes.

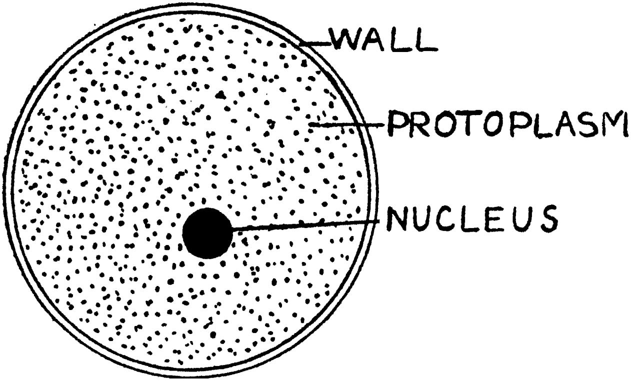


FIG. 42.—A human egg magnified to show the structure. Actually it is about equal in diameter to one of the full stops on this page.

Since the human egg and the Amœba *have practically the same form and apparent structure, why is it that the* Amœba *can produce only another* Amœba *whilst the human egg gives rise to the most complex of all creatures?*

The essential difference between the two cells lies in their nuclei. To make this difference understandable we will consider the detailed structure of the nucleus of a human egg all set to begin development into an embryo.

When the nucleus is highly magnified it is seen to be composed of 48 separate parts called *chromosomes* (Fig. 43). Each chromosome can be visualised as a string with a number of beads of assorted sizes threaded on to it. The structures which in the living chromosome correspond to the beads are called *genes* (Fig. 44). (The genes are not separately visible under any optical microscope but American scientists recently claimed to have seen them by means of the electron microscope.

Usually chromosomes prepared for microscopical examination have the sausage-like shape shown in Fig. 43.)

Some of the 48 chromosomes contain many genes and are therefore long. Others with only a few genes in them are short and stubby. Actually because each variety of chromosome contains a constant number of genes it has both a distinct length and shape by which it can be recognised. The chromosomes differ from one another not only with respect to the number of genes they contain but also with respect to the

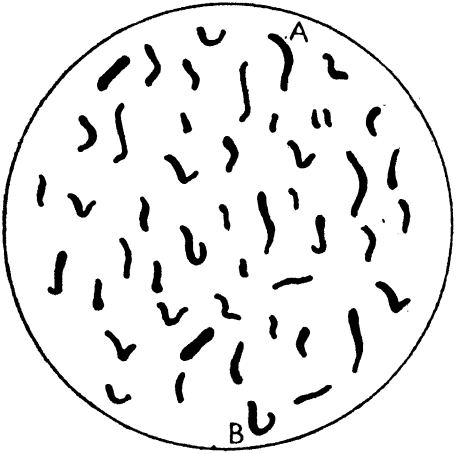


FIG. 43.—The 48 chromosomes in a fertile human egg. There are really only 24 different types of chromosomes in the egg, two of each being present.

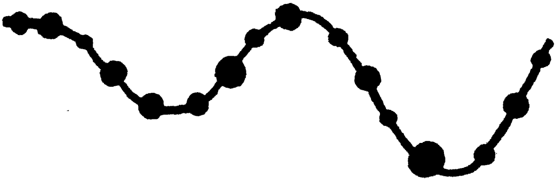


FIG. 44.—How a single chromosome might look if magnified sufficiently to show the separate genes.

nature of their genes. For example, the genes on chromosome A in Fig. 43 are quite different from those on chromosome B and as we shall see they perform totally different functions.

This description applies to any fertile human egg. Every normal human egg ready to begin development contains a similar set of genes arranged on 48 chromosomes. It is these genes which determine that the egg shall develop into a human being. For although they are exceptionally small—the biggest is only about a millionth of an inch wide—genes have most remarkable properties. Between them they are believed to control the development of all the organs and other structures which make up a living person.

In this light the great difference between the nucleus of the human egg and the nucleus of the *Amœba* is understandable. The former contains probably more than 20,000 genes highly organised and integrated to perform a multitude of functions : the latter apparently contains relatively few genes with limited powers.

As might be expected there are considerable structural differences between the protoplasms of the human egg and the *Amœba*. And as we shall see these too are important in determining the different behaviour of the two organisms.

The nucleus shown in Fig. 43 seems to be made up not of 48 different chromosomes but of 24 different pairs, the members of each pair being identical in shape and length. Is this accidental ?

No. In every fertile egg each kind of chromosome is represented twice. Thus in the fertile egg of the rabbit there are 22 pairs of chromosomes, in the egg of the fruit-fly 4 pairs and so on. The reason for this is fundamental to an understanding of the mechanisms whereby evolutionary changes are believed to have taken place. It will therefore be explained in detail.

A single *Amœba* is capable of reproducing by the simple process of dividing into two, but among higher forms of animal life the co-operation of two separate individuals is necessary before reproduction can occur. These two individuals are usually dissimilar, being styled male and female.

The main distinction between these sexes lies with the organs specially set aside for breeding. We shall describe here the essential feature of the human breeding organs which are typical of mammals in general.

The vital breeding organs are the reproductive glands of which there is a pair in each sex. Those of the female are called *ovaries,* those of the male *testicles.*

The ovary of an adult woman is a white bean-shaped organ about an inch long bearing on its surface numerous tiny projections (Fig. 45). About every 8 weeks one of these projections bursts, setting free a ripe egg. This usually happens alternately in each ovary with the result that about every month one or the other of the ovaries sets free an egg. This looks like the fertile egg shown in Fig. 42 but it differs in one important respect. Its nucleus is composed of only 24 chromosomes instead of 48, i.e. there is only one of each of the 24 basic chromosomes instead of a pair as in the fertile egg. The significance of this will be explained shortly.

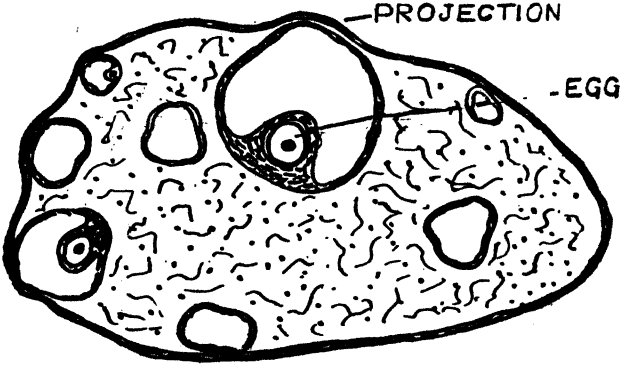


FIG. 45.—A section through a human ovary showing the projections in which the eggs develop.

The testicles of the male are each composed of thousands of coiled tubes in which arise minute structures called *sperms.* Each sperm, which consists chiefly of a rounded head fitted with a whip-like tail, measures about one-thousandth of an inch in length (Fig. 46). The head is made up of 24 tightly packed chromosomes similar to the set found in the egg. The sperm is in fact little more than a nucleus with a tail.

Now when the act of mating occurs one of these sperms—among many millions set free by the male—swims up the reproductive tubes of the female towards the egg. It bores through the egg wall and its head fuses with the egg nucleus to form a composite nucleus in which there are 24 equal pairs of chromosomes—a full set of 24 derived from the male parent via the sperm and a similar set of 24 derived from the female parent via the egg. This is why the nucleus of the egg shown in Fig. 43 has 48 chromosomes arranged in 24 pairs. It is a *fertilised* egg, the union of the egg and sperm nuclei being termed *fertilisation.*

Only an egg which has been fertilised, i.e. has two full sets of 24 chromosomes, can develop into a human being. An unfertilised egg dies.

The importance of the process of fertilisation in the mechanics of heredity and evolution will be obvious when it is remembered that it is the genes in the nucleus of the fertilised egg which control the characters of the organism into which the egg develops. Fertilisation ensures that half the genes come from the mother, the other half from the father. This means that in principle the two parents have an equal influence on the physical nature of their children.

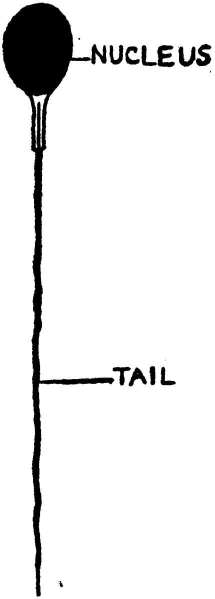


FIG. 46.—A human sperm.

Since the female contributes all the protoplasm of the fertilised egg as well as 50 per cent of the genes, it might be expected that her influence would be greater. But generally this is not the case. The genes are all-important in determining inheritance and by the act of fertilisation the provision of genes is equally shared by the parents.

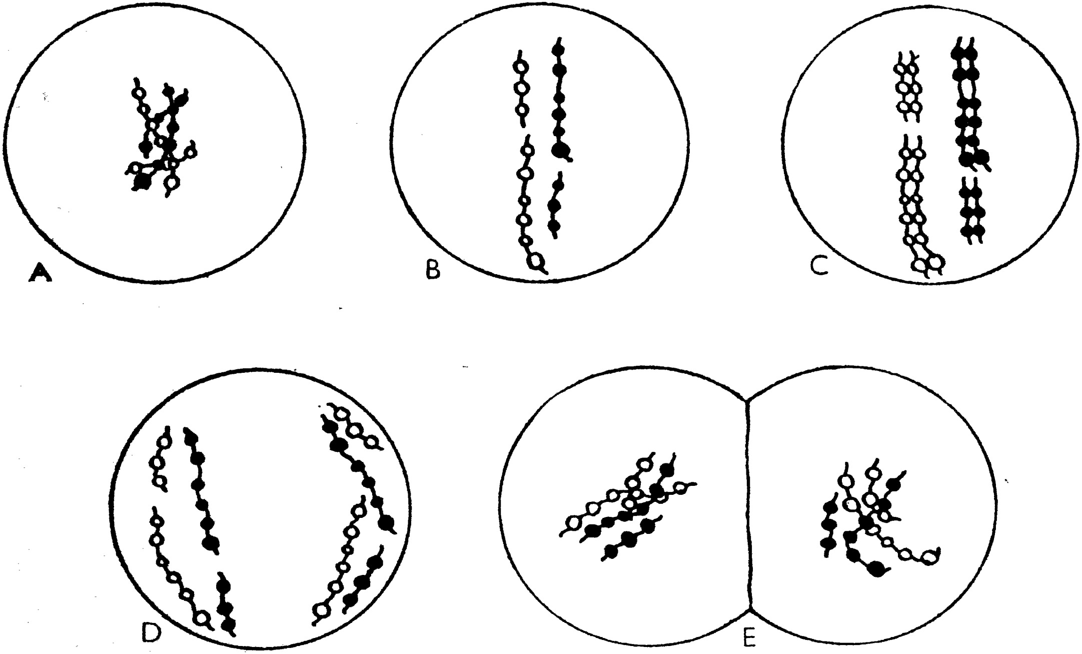


FIG. 47.—Division of a fertilised egg to form two similar cells. Only two of the 24 pairs of chromosomes are shown. The maternal genes are shown black, the paternal ones white.

What happens after the fertilised egg has got its full quota of genes?

The egg begins to divide repeatedly so that from the one cell many cells arise. We will consider its first division in detail. In Fig. 47, which pictures the process, only two of the 24 pairs of chromosomes are shown for the sake of clarity and the *maternal* and *paternal* sets—the 24 chromosomes derived from the mother and father respectively—are differently coloured. (The behaviour of the other 22 pairs is just the same.)

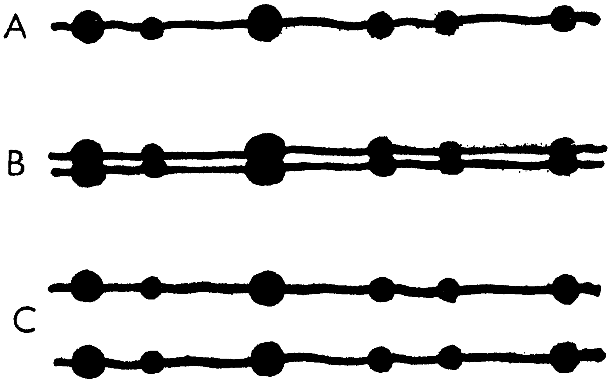


FIG. 48.—Division of a chromosome gene by gene to produce two identical chromosomes.

The chromosomes which are normally clumped together in the nucleus (A) spread themselves out across the middle of the cell (B). Then each gene in each chromosome divides to form exactly similar genes, with the result that each chromosome comes to consist of two exactly similar halves each with the same number of genes arranged in the same order (C). This gene-by-gene division is pictured in Fig. 48.

The two halves of each split chromosome move to opposite ends of the egg cell so that at each end there is a full set of 24 chromosomes derived from the original set inherited from the mother and a similar set derived from the father (Fig. 47 (D)).

A wall then develops right across the middle of the cell substance separating these two lots of 48 chromosomes (E). But the cell halves so formed do not separate as they do when the *Amœba* undergoes cell division. Instead they remain attached and each grows to the size of the original egg with the result that the one-celled egg comes to consist of two cells which are exactly alike containing identical sets of chromosomes and genes. The whole process is repeated successively, the two cells dividing to form four and so on until the 100,000,000,000,000 or so cells which eventually make up the body of the grown man or woman are formed.

New chromosomes can arise only as the result of the gene-by-gene division of pre-existing chromosomes. So no matter how many times the original 48 chromosomes in the fertilised egg are reproduced they normally retain their exact identity with respect to both the quantity and quality of the genes composing them. All the cells which arise from the fertilised egg are therefore identical as far as their nuclei are concerned. In spite of this, however, their subsequent behaviour varies. Some form the skin and bones: others become stretched out and joined to form muscles; some separate from the main mass and float about in a liquid so forming the blood: others form the nervous system: others become the light-sensitive cells of the eyes and so on. In other words, cell formation in the human embryo is quickly followed by *differentiation*—specialisation for different jobs. It is in this process of differentiation that the genes come into action. They decide what ultimate form a new cell shall have and how it will carry out its functions.

Briefly what happens is this:

The full complement of genes is present in each cell of the developing infant but most of them appear to lie dormant throughout the cell's life. Only a few genes produce their full effect in any one cell. And in the different types of cells different genes are brought into play. Thus in the cells forming the skin genes causing the growth of hair come into action, whilst in the cells forming the surface of the tongue these genes remain dormant. In theory there is no reason why hair should not grow on the tongue if the hair-producing genes in the cells forming the tongue's surface could be stimulated into action. Similarly there is no reason in theory why the tastesensitive cells present in the tongue should not arise in the skin as the genes responsible for them must be present, though dormant, in the cells of the skin.

These particular abnormalities—chosen as examples because they are so simple—do not occur. But other abnormalities due to the same fundamental cause—the stimulation of genes in the wrong place—are not uncommon. The best examples are provided by certain cancerous growths which occur in women. These tumours, which may be as big as a coconut, usually contain great quantities of hair, imperfectly formed teeth, nails and irregular masses of bone and cartilage.

It is important at this stage to note that very early in the development of the embryo a clump of cells is set aside in an undifferentiated condition to form the future reproductive glands—ovaries or testicles as the case may be. Like the rest of the cells of the body each cell of this clump—usually known as the *germ-plasm*—contains the full set of 24 pairs of chromosomes. From these chromosomes are formed the nuclei of the *germ-cells*—eggs and sperms—which give rise to the next generation. Whole sets of genes are thus passed on from one generation to another with the result that the physical features of the human race remain basically the same. It is true, for reasons which will be apparent later, that children always differ in details from their parents, but generally speaking in the human species as in all other organisms " Like begets like ".

If the cells of the germ-plasm each have 24 pairs of chromosomes—48 in all—how is it that the eggs and sperms derived from these cells each have only a single set of 24 chromosomes?

When eggs and sperms are being produced a special kind of cell division occurs reducing the number of chromosomes from 24 pairs to 24 in each case. The fertilised egg, formed by the union of an egg and a sperm, therefore contains only the customary 24 pairs. This reduction process ensures that each generation starts off with the number of chromosomes typical for the species. Without it the chromosome number would be doubled in each generation and genetic chaos ending in the extinction of the species would result.

Fig. 49 shows the principle of this reduction division as it occurs in the formation of an egg from a germ-plasm cell of the ovary. (The process in sperm formation is essentially similar.) Without a working knowledge of it the mechanism of evolution cannot be properly understood.

The 24 pairs of chromosomes pair up gene for gene, each maternal one with its paternal fellow. (Only two of the pairs are shown in the figure.) Each pair then separates, the members moving to opposite ends of the cell. The cell is then nipped across to give rise to two separate cells, one of which becomes an egg with 24 chromosomes.

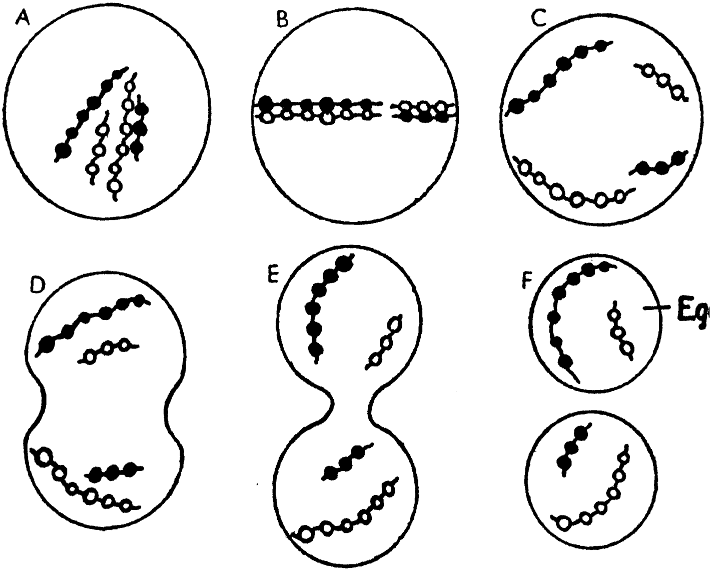


FIG. 49.—Ovary cell undergoing division to produce two similar cells one of which becomes an egg. Only two of the 24 pairs of chromosomes are shown. The maternal genes are shown black, the paternal ones white.

When the chromosomes separate after pairing it is purely a matter of chance whether they go to one end of the cell or to the other so that the egg contains some maternal chromo-

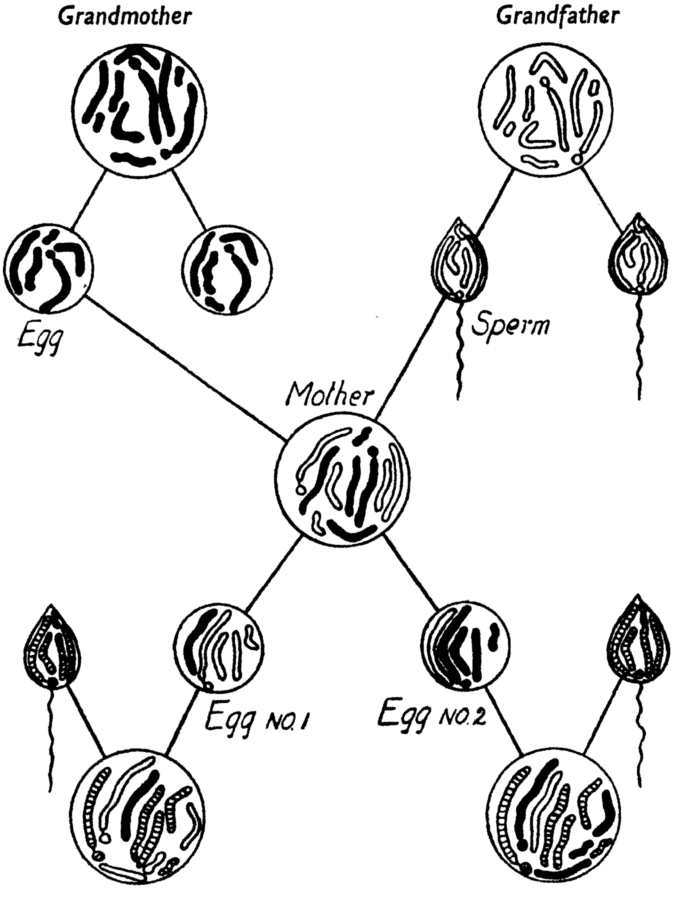


FIG. 50.—The effect of random assortment of chromosomes at germ-cell formation. The grandmother's chromosomes are shown black and the grandfather's white throughout.

somes, i.e. some derived from the mother of the female producing the egg, and some paternal chromosomes which are derived from the father of the female producing the egg. The operation of this process with its highly important hereditary consequences is shown in Fig. 50, which for the sake of clarity represents a hypothetical organism with only five pairs of chromosomes. Egg No. 1 contains only one chromosome (the black one) derived from its grandmother whilst it has four chromosomes inherited from its grandfather. Conversely, chromosomes from the female grandparent predominate in egg No. 2.

This means, of course, that the effect which a grandmother or grandfather exerts on the child arising from the egg is purely a matter of chance. It is in fact possible, as a further examination of Fig. 50 will show, for an egg to inherit no chromosomes at all from one grandparent. The laws of probability make such a happening very unlikely, especially in the human species where the chromosome number is high, but the fact that it is possible highlights the stupidity of attaching social importance to distant ancestry.

But surely if the two chromosomes in each pair are exactly *alike it will not make the slightest difference to the future child which member goes into the egg?*

To clear up this question—for, as we shall see, the answer to it is of vital importance in the evolutionary process—we shall consider a single imaginary pair of chromosomes which are pictured each as a string of five genes in Fig. 51.

Each gene has a particular character to control and in Fig. 51, which it must be stressed is purely fictional and invented for the purpose of easy explanation, the five characters are named. If we imagined the chromosome as a strip of wood with five holes bored in it each of different width (Fig. 52) then the genes would correspond to five pegs cut so as just to fit these holes. Because the pegs are of different sizes each would fit only in its proper place (remember we said that the position of each gene in the chromosome is constant) and it would be impossible for any one peg to be present twice in our model chromosome. But suppose we had another peg exactly the same size as say peg No. 3 but made of white wood instead of black. Then it would be possible for our model chromosome to obtain either of these model genes. The two pegs would represent a pair of interchangeable genes either of which, but not both, could be present in the chromosome.

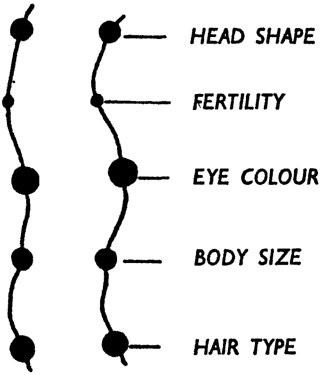


FIG. 51.—Imaginary pair of chromosomes showing the character which each gene controls.

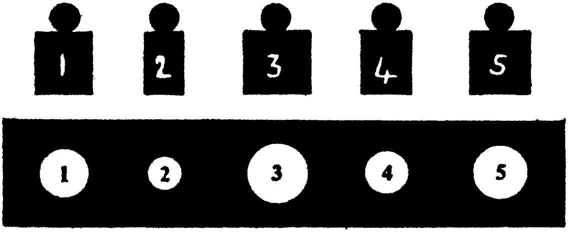


FIG. 52.—Model of a chromosome.

Now since each gene controls one or more characters we should expect that if the two members of an interchangeable pair of genes are slightly different (as the two pegs differ in colour) then the characters they give rise to should be slightly different. According to Fig. 51 we have visualised gene No. 3 as controlling eye colour. What could happen in real life is that if the pair of chromosomes we are considering each contained the gene corresponding to the black peg, the egg carrying them would give rise to a child with brown eyes. But if instead each of the chromosomes contained the gene corresponding to the white peg the resulting child would have blue eyes.

These are the sort of differences which normally exist between two chromosomes which look exactly alike under the microscope. The genes they contain are *basically* the same, e.g. gene No. 3 in our model chromosome always controls eye colour, but for each gene position on the chromosomes there are alternative genes which modify the basic characters.

We must not carry this comparison of the genes with the pegs so far that it gives rise to the impression that genes may occur separately waiting for the chance, as it were, to slip into an uninhabited space in a chromosome. So far as we know genes can exist only as an integral part of a chromosome.

The actual state of affairs is that in every cell of some individuals of a species a particular place in a particular chromosome is occupied by one gene, whilst in other individuals a different gene producing slightly different effects is present there.

It is thought that in the full single set of 24 human chromosomes there are between 20,000 and 40,000 genes each with a different function. Since most and perhaps all of these genes exist in interchangeable forms it is clear that the chances of any two individuals having exactly the same allotment of genes will be very small. This explains why the individuals of the same species—men for instance—though basically the same differ sufficiently in detail as to be separately recognisable.

We can see now why it does matter which member of an apparently identical pair of chromosomes goes into the egg. Fig. 53 shows how the eye colour of a child with a brown-eyed mother and a blue-eyed father entirely depends on this chance sorting out of the chromosomes at egg formation. In this case the two chromosomes carrying the genes for eye colour in the mother look alike but in fact one contains a gene producing brown eyes (*B*), whilst the other contains a gene producing blue eyes (*b*). If the chromosome carrying the brown-eyed gene happens to move into that end of the ovary cell which becomes the egg, the resulting child is brown-eyed.

If the other chromosome gets in instead the child has blue eyes.

This fact that individuals of the same species carry slightly different genes also explains why brothers are not exactly alike. Because of the entirely random sorting out of chromosomes at the formation of every egg and sperm there is very little likelihood that two fertilised eggs will ever start off with identical gene complements.

How then do you account for the exceptional likeness seen in twins?

We have seen how the fertilised egg rapidly divides to form a structure made up of two identical cells each with exactly the same genetic constitution. Well occasionally, for reasons not properly understood, these cells separate and subsequently behave as individual fertilised eggs. They start development not only with the same genes but with exactly the same type of protoplasm, and the result is a pair of infants so alike as to merit the name *identical twins*.

Occasionally the splitting of the fertilised egg to form identical twins is incomplete and the twins are born joined together in various states of intimacy depending on the degree of incompleteness of the split. Such *Siamese twins* may be so completely merged that they share a single head, heart and stomach whilst each possesses a full set of limbs or they may be almost entirely separate physiologically, being joined only by the buttocks.

Now it is easily observed that some twins are not particularly alike, often, in fact, being so dissimilar as to belong to different sexes. Such twins arise not by the division of a single egg but by the separate fertilisation of two distinct eggs by two distinct sperms.

Usually the human ovaries release only one egg at a time, but sometimes two are shed simultaneously and if both are fertilised they may complete development and be born together.

The genetic constitution of such *fraternal* twins, as they are called, is governed by the usual random assorting of the chromosomes at egg and sperm formation. The degree of physical resemblance between them is therefore unlikely to be any greater than it is between other brothers and sisters of the same family.

It is significant that whereas fraternal twins can be of different sexes, twins produced by the division of a single egg always belong to the same sex.

In Fig. 53 you show the ovary cell of the brown-eyed mother as containing a chromosome bearing the gene for brown eyes and a chromosome bearing the gene for blue eyes. This means that the egg from which she developed had these two genes in it. Why didn't she develop eyes a mixture of blue and brown in colour?

It so happens that the gene which brings about the brown colour is " stronger " than the gene which causes blue eyes. The gene for brownness blankets the action of the gene for blueness, which seems to lie dormant in the cells of the iris of the eye producing no effect. The phenomenon is called *dominance*. In our example the gene for brown eyes is said to be *dominant* to the gene for blue. The gene for blue eyes is said to be *recessive* to the gene for brown. (Actually because other genes affect eye colour brown is not always absolutely dominant to blue but it usually is.)

It should be pointed out at this stage that far more is known about the genes of lower animals and plants than about the genes of man. The reason for this is that genes are so small that they cannot be seen with certainty through any microscope yet devised. Their nature and behaviour in heredity can therefore be determined only by observing their effects—i.e. the characters they give rise to—over many generations under strictly controlled conditions. This is impracticable in the case of human beings because people cannot be kept under observation indefinitely, and in any case the time taken for a sufficient number of generations to arise would be too long. The best examples of dominance are therefore known from studies of insects, poultry, rats and domestic animals to which these drawbacks do not apply so strongly.

It must not be thought, however, that inferences regarding human heredity drawn from animal and plant studies are far-fetched. There is an ever-growing mass of evidence to show that the chromosome and gene mechanism of heredity is essentially the same for all organisms including man.

Experimental evidence that one gene really can suppress the action of another is provided by a study of the interchangeable

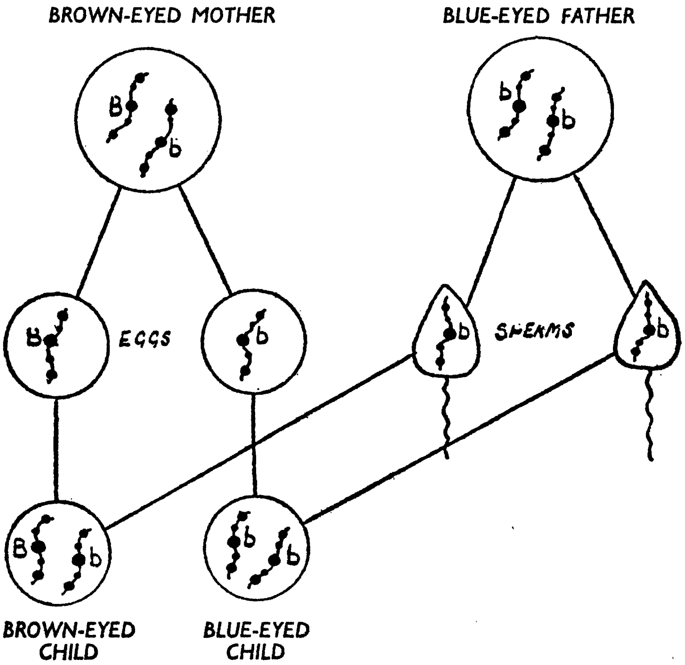


Fig. 53.—The inheritance of human eye-colour. The *B* gene producing brown eyes suppresses the *b* gene which produces blue eyes, when both occur together in the same cell. Only the pair of chromosomes concerned is shown. The large cells represent germ-cells of the ovary and testicle respectively.

pair of genes controlling the development of horns in cattle. Some breeds of cattle like the Galloways are hornless; others like the Shorthorns are horned. If a Galloway bull is crossed with a Shorthorn cow the resulting calves are usually hornless because the gene for hornlessness is dominant to the gene for horn-production. Occasionally, however, some of the cross-bred bull calves develop small horns called *scurs*, proving that the gene for horn-production is present but suppressed.

As an example of dominance among plants we may consider the interchangeable pair of genes controlling height in peas. Some varieties of pea-plants carry a gene which makes them tall. Others carry an alternative gene which makes them dwarf. If the two types are crossed to give rise to seeds which contain both genes the plants into which these seeds develop are all tall.

It will be seen from these examples that with respect to a particular pair of genes a fertilised egg—and hence the organism to which it gives rise—can be " pure " or " mixed ". (The technical terms for these two conditions are *homozygous* and *heterozygous* respectively.) Thus a fertilised egg containing two genes for brown-eye colour could be said to be pure for that gene, whilst an egg with only one gene for brown eyes and the other for blue eyes would be mixed.

In all the mixed cases we have so far considered one gene of the interchangeable pair has been dominant and the other dormant, but this is by no means always so. Take the case of the cross between white and red Shorthorn cattle, for instance. Each cell of a red Shorthorn cow contains a pair of chromosomes on each member of which is lodged a gene which determines that the hair of the coat shall be red. The corresponding chromosomes in the cells of a white Shorthorn bull each carry a gene which determines that the hair shall be white. The fertilised egg resulting from the mating of these two animals has a gene of each type in it and the resulting calf has a red roan coat—a mixture of red and white hairs. In this case then both genes exert an overall effect.

It is the custom to despise human examples of this mixing of genes when skin-colour happens to be the character affected —" half-caste " being almost a term of abuse. It is a quite illogical custom for even if our skin-colour genes happen to be pure we all carry some genes in the mixed or impure condition. We are all to some extent half-breeds under the skin.

If genes are too small to be seen how was their existence discovered?

The idea that the individual physical characters of an organism are each controlled by a specific particle (what we now call a gene) arose from breeding experiments carried out by an Austrian monk called Gregor Mendel in the middle of the last century. It is most instructive to follow his original train of thought, but because Mendel worked entirely with plants and this book has so far dealt mainly with animals it will be easier for the reader if we first apply Mendel's arguments to a more recent series of experiments in which animals—Andalusian fowls—were used.

The Andalusian breed of poultry exists in two pure strains—white and black. Apart from this colour difference the two strains are exactly alike. When two white birds are mated they produce only white offspring whilst two black fowls produce only black offspring. If the two strains are crossed, however, e.g. if a white hen is mated with a black cock, all the offspring have white feathers heavily sprinkled with black pigment giving a slaty-blue effect—the well-known Blue Andalusian.

At first sight, then, it would appear that the two colour characters of the parents have simply mixed on a fifty-fifty basis much as two colours might be mixed on an artist's palette. This is what common sense would lead us to expect, but if we carry the experiment a stage further by mating two of these blue birds we find that this simple explanation will not do. For instead of producing just more blue fowls the cross also yields some white and some black. Furthermore, if we repeat the experiment of crossing blue Andalusians many times and count the total number of white, black and blue birds obtained we find that a simple numerical relationship exists between them. Typical figures for such a series of crosses might be 510 white birds, 1,040 blues and 498 blacks, whilst another breeder repeating the series might get 515 whites, 1,003 blues and 506 blacks.

The basic proportion of 1 white : 2 blues : 1 black is so obvious in each case as to suggest that some simple clear-cut mechanism controls the inheritance of colour in Andalusian fowls. If we seek a comprehensive theory to account for such results we find that only one—the theory first developed by Mendel—is satisfactory.

We are forced to assume that the colour of the blue Andalusian is due to the presence of two factors—a factor for whiteness, which we will call *W*, and a factor for blackness, which we will call *B*. Both factors were in the egg from which the fowl developed being derived from the white and black parent respectively (Fig. 54). These two factors separate when a blue hen produces eggs so that 50 per cent of the eggs it sheds from the ovary contain only the factor for white colour whilst the other 50 per cent contain only the black colour. Similarly the sperms produced by a blue cock-bird are of two sorts—one containing the factor for whiteness, the other the blackness factor.

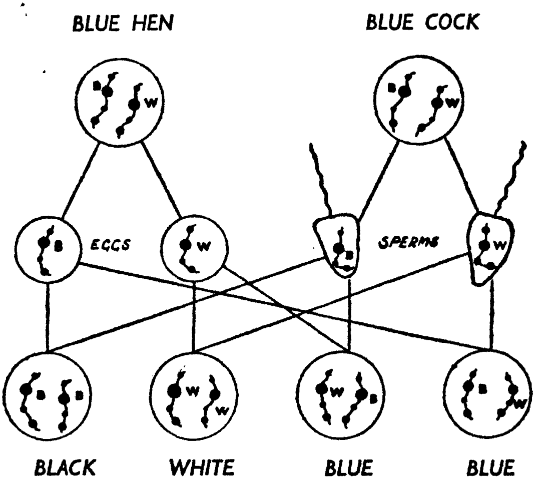


FIG. 54.—Mating of two blue Andalusian fowls to give a second generation. The genes for blackness and whiteness are represented by the letters *B* and *W* respectively. Only the chromosomes bearing the colour genes are shown.

On this basis we can see from Fig. 54 that by the laws of probability matings between two blue Andalusians should produce birds in the proportion of 1 white : 2 blues : 1 black—the actual rates obtained by the breeders. (Such proportions will show up regularly only when large numbers of matings are concerned, for only then can the laws of probability operate significantly. You can prove this for yourself by repeatedly tossing a coin and writing down the result. If you toss the coin five times you may well get a result of 4 heads : 1 tail, but as the total number of tosses increases, the proportion will get progressively closer to the expected 1 : 1 ratio. It is futile therefore to expect a 1 : 2 : 1 Mendelian ratio among four chickens produced by mating a pair of Blue Andalusians. Even if such a result were obtained no general significance could be attached to it.)

We can easily test this theory of Mendel's by making certain predictions and seeing if they are fulfilled. The black fowls arising from our mating of two blues each contain—according to the theory—two factors for blackness and none for whiteness, so when two of them are mated they should produce only black offspring. This is found to be the case. These black birds derived from blue parents are every bit as pure for colour as a flock of black Andalusian which have never been crossed with whites. The white birds derived from blue parents are equally pure for their colour.

But what about the blues descended from blue parents? Since they also contain one factor for blackness and one for whiteness they should always be capable of producing both black and white offspring when mated as well as more blues. Experiment shows that this is so. It is impossible to breed a flock of blue Andalusians that will always breed true to type. As Mendel's theory explains, they are bound to produce some pure black and some pure white birds.

Now let us see if this theory holds for a case where dominance complicates the issue. Again we will choose an example from poultry breeding.

Some types of fowls have the large single comb shown in Fig. 55 whilst others have the smaller so-called rose comb. Matings between single-combed fowls produce nothing but single-combed offspring whilst matings between rose-combed fowls yield only rose-combed young.

When a single-combed cock is mated with a rose-combed hen the young do not have combs intermediate in shape and size as might be expected. Instead they all have rose combs and as far as this character is concerned they are indistinguishable from the pure rose-combed stock. Further breeding shows, however, that they are really quite different. For when two of these half-bred rose-combed fowls are mated they give rise to birds, some with rose combs and some with single combs.

Analysis of many such matings shows that three times as many rose-combed birds are produced as single-combed.

How does this fit in with the Mendelian theory ? Fig. 56 shows what we should expect to happen. It will be seen that a 3 : 1 ratio is exactly what would be expected when one of a pair of characters is dominant to the other.

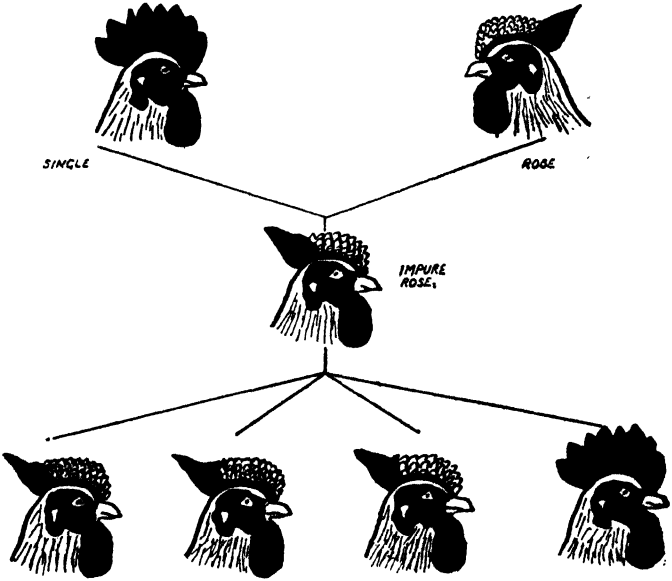


FIG. 55.—The mating of single- and rose-combed fowls always produces fowls with rose combs. But when two of these impure rose-combed birds are mated both rose- and single-combed fowls arise in the second generation—in the proportion of three rose to one single when a large number of matings are statistically examined.

Again we can test this theory by making predictions. It will be seen that though the rose-combed birds of this second generation all look alike they should in theory be different. One third of them should be pure rose-combed whilst the other two-thirds should be half-bred like their parents and therefore certain to produce some single-combed birds when mated themselves. Experiment shows that these expectations are fulfilled.

Thousands of other breeding experiments with creatures of widely different natures have confirmed that the inheritance-by-genes theory is generally valid throughout the animal kingdom. It is equally applicable to plants, and indeed it was as a result of plant-breeding experiments that Mendel formulated his theory.

It is not surprising that the same system should operate throughout both kingdoms, for the sexual organs of plants parallel those of animals. A ripe seed contains a fertilised egg corresponding essentially to that of an animal being formed by the union of a female egg-cell and a male cell called a *pollen grain* instead of a sperm. The egg in turn contains a nucleus made up of chromosomes essentially similar in structure to those of animals.

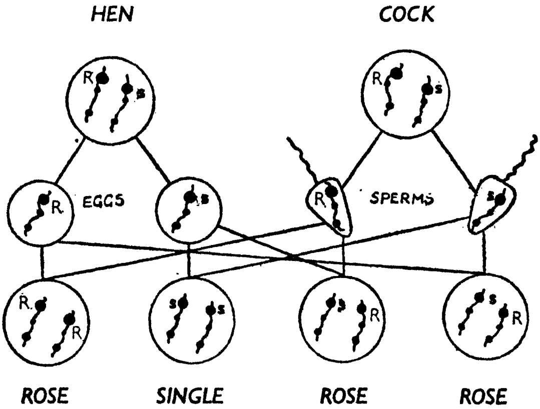


FIG. 56.—The effect of mating two rose-combed fowls also carrying the recessive gene for single comb. (It is a useful convention to symbolise a dominant gene by a capital letter and a recessive gene by a small letter.)

As an example of gene inheritance in plants we cannot do better than choose one of Mendel's original experiments in which he studied the size of pea plants.

There are some tall varieties of pea plants that produce seeds which always develop into tall plants themselves. Tallness is in fact a constant inherited feature of these varieties and provided the strain is kept pure—i.e. if pollen from only tall plants is used in fertilising them—they will remain tall for as many generations as an experimenter has patience to produce.

There are other varieties which are just as characteristically dwarf. They go on producing generations of more dwarfs so long as the stock is kept pure.

Mendel decided to cross these two varieties. He found that the hybrids were always tall, being in fact indistinguishable from pure-bred tall pea plants. Tallness in peas then behaves just like the rose-comb character in fowls, completely dominating the alternative feature.

Next Mendel mated a large number of these hybrids, taking pollen from some to fertilise the rest. He carefully collected all the seeds which formed in the pods and planted them. In this second generation which resulted there were both tall and dwarf plants in the proportion of three talls to one dwarf. If in Fig. 56 we regard the sperms as pea pollen grains and the genes *R* and *s* as controlling tallness and dwarfness respectively we can see why Mendel found that one-third of the tall plants in his second generation of peas were pure for tallness whilst the other two-thirds were hybrids.

Having satisfied himself that such a pair of alternative characters as tallness and dwarfness are controlled by independent factors (now called genes) which separate when the sex cells are produced, Mendel went a stage further.

Instead of concentrating on a single pair of characters he studied two pairs at once. Again we shall find his arguments easier to follow if we apply them first to an exactly parallel experiment in which animals were used.

In cattle black coat colour is dominant to red and a uniformly coloured coat is dominant to a spotted coat. The effect of this when a red spotted cow is crossed with a uniformly black bull of a pure strain is that all the calves are uniformly black. Now what happens if we mate a large number of these hybrids which though uniformly black in appearance must be carrying the genes for both spotted coat and redness? The result is that four types of calves are produced in a definite proportion of 9 black and uniform: 3 black and spotted: 3 red and uniform : 1 red and spotted. Let us see how all this fits in with Mendel's gene theory.

In Figs. 57 and 58 the dominant genes for blackness and uniform coloration are represented by the letters *B* and *U*

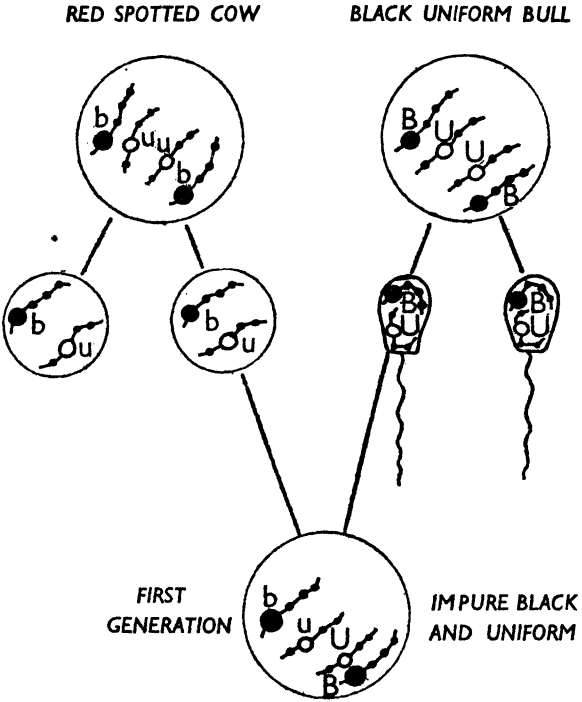


FIG. 57.—Explanation of the result of crossing a red spotted cow with a uniformly black bull. The dominant genes for blackness and uniform colour are represented by *B* and *U* whilst the corresponding recessives for red and spotted are shown as *b* and *u*. Only the chromosomes involved are represented.

whilst, following the usual convention, the corresponding recessive genes for red and spotted are shown as *b* and *u*. (There are 19 pairs of chromosomes in cattle but only the two pairs carrying the colour genes we are concerned with are represented in the diagrams for the sake of clarity.) Fig. 57 represents the initial cross between the red spotted cow and the uniformly black bull. It will be remembered that in both sexes the cells of the germ-plasm—like the rest of the body cells—contain two of each kind of chromosome. So in this case the ovary cells of the red spotted cow will each contain two chromosomes carrying the *b* gene and two carrying the *u* gene. Such a cell divides to form eggs each equipped with only one of every kind of chromosome and therefore in this case only one *b* gene and one *u* gene. Because a similar chromosome-reduction division occurs at sperm-formation the sperms of the uniformly black bull will also be all alike with one *B* gene and one *U* gene.

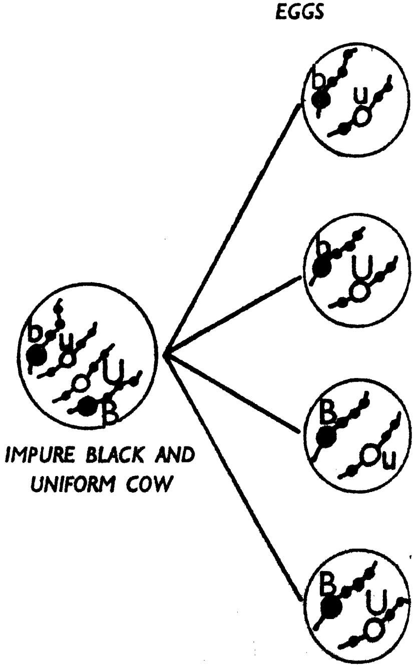
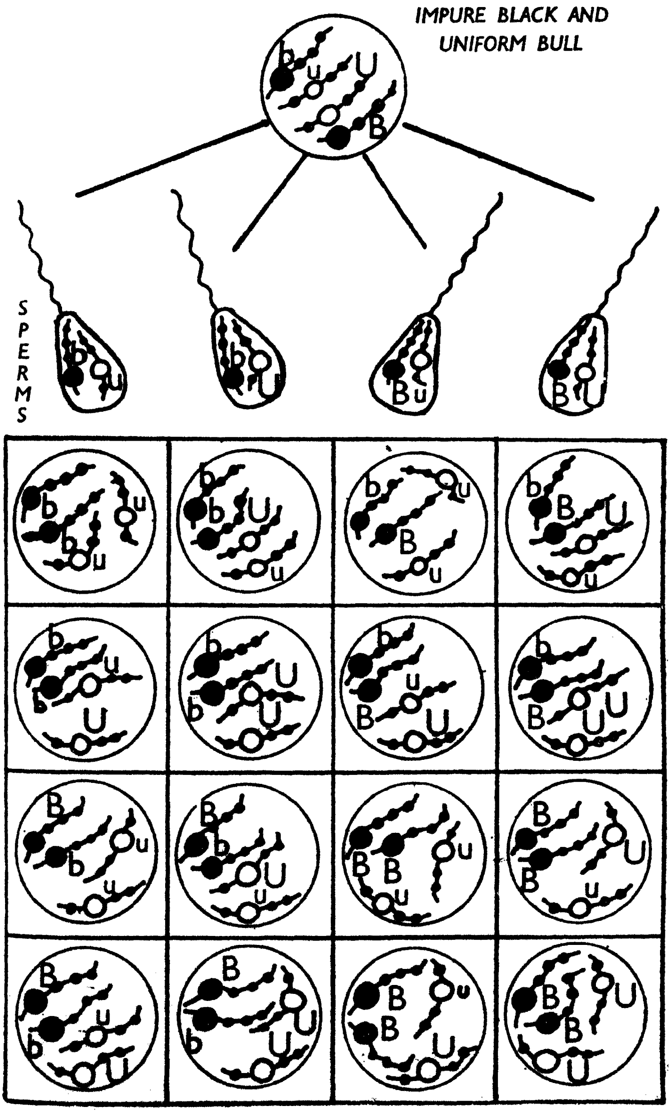


Fig. 58.—Explanation of the result of crossing



two beasts impure for black and uniform coloration.

It follows then that any egg from a red spotted cow fertilised by a sperm from a pure-strain uniformly black bull must contain one *B* gene, one *b* gene, one *U* gene and one *u* gene. Such an egg develops into a hybrid beast which to all appearances is as uniformly black as its father.

We now have to consider the effects of crossing two of these hybrids.

It has been pointed out that chance alone decides which member of each pair of chromosomes goes into a particular egg or sperm. Since this is so, hybrid cows of the kind we are considering will produce four different types of eggs whilst hybrid bulls of the same kind will produce four different kinds of sperms. These are shown in Fig. 58. They have the gene formulas *bu*, *bU*, *Bu* and *BU* respectively.

Again at fertilisation it will be purely a matter of chance which type of egg is fertilised by which type of sperm. So, as Fig. 58 shows, 16 different unions are possible. If these are more closely examined it will be seen that they produce 9 kinds of fertilised eggs which differ from each other as regards their colour-gene content. They are: *BbUu* (4 eggs), *Bbuu* (2 eggs), *bbUu* (2 eggs), *BbUU* (2 eggs), *BBUu* (2 eggs), *bbuu* (1 egg), *bbUU* (1 egg), *BBuu* (1 egg), *BBUU* (1 egg). The dominance of *B* and *U* decides that these eggs will develop into calves of the following colour:

9 uniformly black—*BBUU*, *BBUu* (2), *BbUU* (2), *BbUu* (4).
3 black and spotted—*BBuu*, *Bbuu* (2).
3 uniformly red—*bbUU*, *bbUu* (2).
1 red and spotted—*bbuu*.

These, as we have seen, are the proportions obtained in practice when a sufficiently large number of calves are reared to allow the laws of probability to operate fully.

Mendel, without knowing anything about the existence of chromosomes, worked out the basis of an exactly similar two-character cross in peas. The two alternative pairs of characters he studied were seed colour—peas can be either yellow or green—and seed shape—peas can be either round or wrinkled. Yellow and round are dominant to the other two and from many experiments Mendel got a ratio in the second generation of 9 yellow and round : 3 yellow and wrinkled : 3 green and round : 1 green and wrinkled.

This confirmed in his mind the *first* law he had deduced from his earlier experiments—*that characters are controlled by specific factors (genes) which are passed on from generation to generation via the germ cells (eggs and sperms).* It also suggested a *second* law, which Mendel later proved to his satisfaction—*that the distribution at egg and sperm formation of the two members of a pair of interchangeable genes is governed purely by chance and is not affected by the distribution of the members of any other pair.* Exactly what Mendel meant by this law is best understood by applying it to a particular case. The process of egg formation in a uniformly black cow of the type pictured on page 102 will serve.

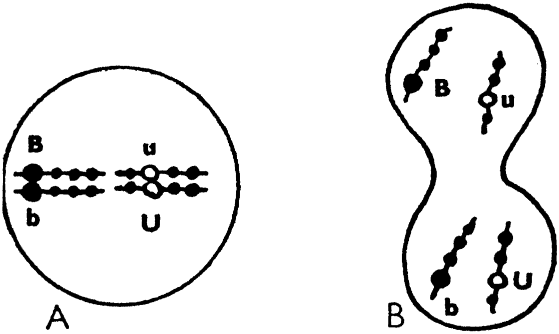


FIG. 59.—Ovary cell dividing by the chromosome reduction process to produce two cells. Only two pairs of chromosomes are shown.

When the ovary cell is dividing by the chromosome-reduction process to form two cells it is purely a matter of chance whether the chromosome with the *B* gene on it or the one carrying the *b* gene goes to the top half (Fig. 59). The fact that the *B* chromosome goes to the top in no way influences the direction taken by the *U*- and *u*-bearing chromosomes. Their distribution is likewise entirely dependent on chance. In other words different pairs of genes sort themselves out quite independently at germ-cell formation.

It is because of this second law that the four types of eggs and sperms shown in Fig. 58 are produced in equal numbers, giving rise when chance is given full play to the 9 : 3 : 3 : 1 ratio.

It was not until long after Mendel's death that his hypothetical "factors" were found to be located on the chromosomes and given the name "genes".

The reader will probably have noticed that most of the characters so far mentioned as definitely gene-controlled are modifications of basic features such as colour of eyes, length of ears and shape of comb. It must be admitted that it has not yet been possible by the experimental methods available to prove beyond all doubt that the basic features themselves, i.e. what makes a dog a dog and a cat a cat, are themselves gene-controlled. The reason for this is a simple one. The existence of such genes could be proved only by breeding experiments between such markedly different organisms as a dog and a cat.

Such crosses have so far proved impossible.

How does Mendel's second law operate in the case of two genes located on the same chromosome?

The answer is simply that it does not operate. To see what happens instead we will consider a particular example—the genes controlling length of hair and coat colour in rabbits.

The English rabbit has a spotted coat and short hair because of the presence of two special genes which happen to be located on the same chromosome (*B* and *T* in Fig. 60). The Angora rabbit carrying the recessive partners of these genes (*b* and *t*) is uniformly white and long-haired.

Fig. 60 shows why a cross between these two types of rabbits looks like a pure English although it carries both recessives.

Now look at Fig. 61, which pictures a mating between two of these impure English rabbits. Clearly only two kinds of eggs and sperms are possible instead of the four which would arise if the genes were on separate chromosomes. This means that we get only three types of young rabbits from such matings in the proportion of 1 pure English : 2 impure English : 1 pure Angora. Because of the dominance of *B* and *T* this would appear to the eyes as a 3 : 1 ratio.

When two pairs of genes are located on one pair of chromosomes in this way they are said to be *linked*. And in crosses they behave as if the two characters were controlled by a single pair of genes giving a 3 : 1 instead of a 9 : 3 : 3 : 1 ratio.

It was purely by good luck that Mendel happened to pick on pairs of non-linked characters when he did the pea-seed experiments which led him to formulate his second law. But the subsequent discovery of chromosomes and consequently of linked genes did not invalidate the law. It simply meant that the way Mendel had originally worded it had to be slightly modified to fit the new knowledge.

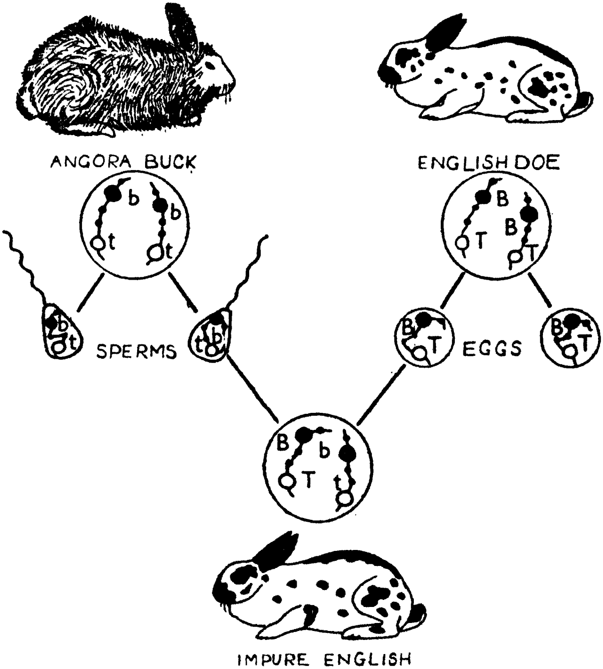


FIG. 60.—The effect of crossing an Angora buck with an English doe. The genes for spotted coat and short hair are represented by *B* and *T* respectively, *b* and *t* being the corresponding recessives for uniformly coloured coat and long hair. Only the chromosomes involved are shown.

Mendel's basic idea that each character is separately controlled by one specific gene has also had to be altered to account for the results of later experiment. The fact is that only rarely does this one-gene-one-character relationship hold. Usually a character is controlled by several genes, though the influence of one of them may predominate. Thus milk yield and coat colour in cattle are each under the influence of several genes. Sometimes, on the other hand, one gene may directly affect two or more characters, e.g. a single gene is known to affect both the texture of the wool and vitality in sheep; a gene which affects eye-colour in certain flies also alters the life-span.

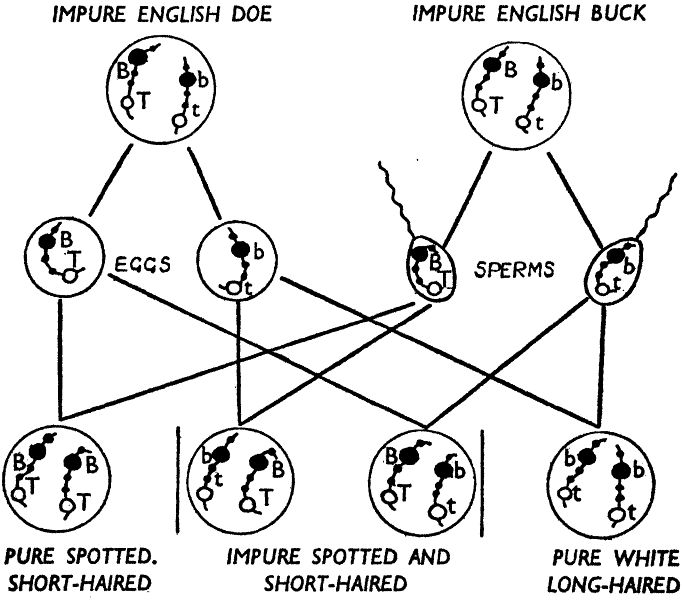


FIG. 61.—Explanation of the result of mating two of the impure English rabbits shown in the previous figure.

As will be stressed later each character is almost certainly affected to some extent by all the genes, this interaction being of the greatest importance in evolution.

Since genes are too small to be seen how can their position on a particular chromosome be located?

The fact that linked genes behave in the special way just described provides the first clue.

Let us suppose we want to find the location of the genes in an animal—an insect for instance—not previously studied in this respect. First we could examine the chromosomes in the animal's developing germ cells. Suppose that we did that and found there were four pairs of chromosomes with the characteristic size and shape shown in Fig. 62. The next step would be to discover which of the animal's characters were controlled by genes in a sufficiently clear-cut way for straightforward study. We could do this by choosing pairs of characters which appeared to be interchangeable and following them through two generations in carefully controlled breeding experiments. We could reasonably assume that those which bred out in a 1 : 2 : 1 ratio in the second generation were Mendelian pairs of the type responsible for plumage colour in Andalusian fowls and that those giving a 3 : 1 ratio were Mendelian pairs showing dominance of the type responsible for comb shape in poultry. We could then test these assumptions by further experiments.

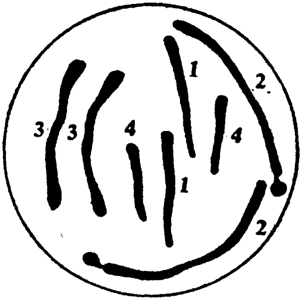


FIG. 62.—An ovary cell of a hypothetical insect showing four pairs of chromosomes.

Having established which characters are simply controlled by genes we could then proceed to discover which genes were on which chromosomes. The first step would be to find out which of our known genes were linked. We could do this by studying two pairs of genes at a time. Those which behaved like the two pairs of genes we examined in connection with coat colour in cattle (see Fig. 58) giving a 9 : 3 : 3 : 1 ratio in the second generation would clearly not be linked. Those behaving like the two pairs of genes we studied in connection with coat colour in rabbits (see Fig. 61) giving a 3 : 1 ratio in the second generation would be linked.

Having found one linked pair—say the gene for eye colour and the gene for wing shape—we would then repeat our previous breeding experiment observing this time not eye colour and wing shape but eye colour and some other character, say body length. The ratio of the types of offspring in the second generation would again tell us whether these two genes were linked or not. By applying this principle so as to cover all the characters which our preliminary experiments told us were controlled by genes we should end up with four columns of linked characters each controlled by an interchangeable pair of genes. These columns might look like this:

LINKAGE GROUPS

Group 1.	Group 2.	Group 3.	Group 4.
Eye colour :	Wing length :	Body length :	Body shape :
red	long	short	fat
blue	short	long	thin
Wing shape :	Fertility :	Bristle shape :	Tail length :
rounded	fertile	simple	short
pointed	infertile	forked	long
Hairiness :	Eye size :	Leg length :	Eye shape :
hairy	big	long	round
not hairy	small	short	oval
Antenna length:	Body colour :		Antenna shape:
long	black		straight
short	yellow		curved
Head shape :			Bristle length :
broad			long
narrow			short
			Tail colour :
			black
			red

These four *linkage groups* would correspond to the four pairs of chromosomes and the next step would be to find which group correspond to which pair.

Now sometimes there are accidents to the chromosomes during cell division. A short piece may be knocked off the end of a chromosome and lost. A specimen of our hypothetical insect developing from a fertilised egg containing a pair of such chromosomes—whose abnormally short length would be observable under the microscope—would be lacking the genes which made up the missing bits.

Suppose we actually found such a specimen and that it was chromosome No. 3 (see Fig. 62) which had the piece missing. If we found that the insect also had colourless eyes instead of red or blue eyes—the normal alternatives—we could tentatively assume that the missing piece had contained the genes controlling the production of pigment in the eye and that therefore the linkage group shown in column 1 probably corresponded to chromosome No. 3. This would be the same as saying that the genes controlling the characters listed in column 1 were all normally located on No. 3 chromosome pair.

In later experiments we might come across an insect which because of a similar accident had lost a bit of the other end of chromosome No. 3. If in this case we found that the characters affected because of the missing genes also belonged to No. 1 linkage group our assumption that the genes corresponding to this linkage group were all on No. 3 chromosome would be considerably strengthened.

Further experimental evidence of this kind might confirm our assumption, and in the course of time we might be able to assign the columns of characters forming four linkage groups to the particular strings of genes forming the four pairs of chromosomes.

It might turn out this way:

The characters forming linkage group No. 1 are controlled by genes located on No. 3 chromosome pair.

The characters forming linkage group No. 2 are controlled by genes located on No. 1 chromosome pair.

The characters forming linkage group No. 3 are controlled by genes located on No. 4 chromosome pair.

The characters forming linkage group No. 4 are controlled by genes located on No. 2 chromosome pair.

How could we then ascertain the relative position of these genes on any particular chromosome? Again a peculiarity of chromosome behaviour at cell division comes to our rescue.

We have seen (Fig. 49) that at germ-cell formation the two members of each pair of chromosomes pair up gene-for-gene prior to the division of the cell which is to form an egg or sperms.

This pairing is actually so intimate that the chromosomes may exchange parts as shown in Fig. 63. This exchange is called *crossing over* because parts of the maternal chromosome cross over to the corresponding paternal chromosome and vice versa.

Now if two genes are far apart on a chromosome there is a greater chance of their being separated by an accidental crossing over than if they are close together. Fig. 63 makes this clear. The two genes A and D will become separated if crossing over takes place at any point in the long space between them but genes B and C will be separated only when the cross-over happens to fall in the very short space between them. Genes A and D will therefore have what is called a higher *cross-over frequency* than genes B and C.

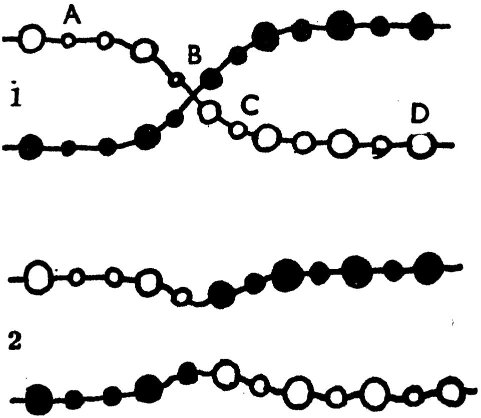


FIG. 63.—Crossing over of genes between a maternal and paternal chromosome.

In general then genes far apart on a chromosome have a higher cross-over frequency than those near together. Conversely two genes with a high cross-over frequency are further apart on the chromosome than two genes with a low one.

Since cross-over frequencies can be calculated from breeding experiments the relative positions of known genes on a chromosome can be determined.

All this and much more has actually been done in the case of a living insect called the *Drosophila* fruit fly (Fig. 64).

This creature, which has been especially widely studied because it lives well under laboratory conditions and breeds rapidly, producing a fully grown generation every ten days, has four pairs of chromosomes corresponding to which four linkage groups have been established by breeding experiments. In addition " maps " showing the location of many known genes on the chromosomes have been drawn up.

Similar linkage groups and chromosome maps have been worked out for other animals and plants. There are, for example, ten pairs of chromosomes in the maize plant and ten known linkage groups.

But the reader must not think all this has been accomplished as easily as our brief sketch of the experimental methods would suggest. That sketch was simplified for the purpose of presenting the pith of what is in fact a most complex argument. We assumed that one capable researcher could take an unworked species and by a series of straightforward steps discover the exact make-up of the chromosomes. This was a great exaggeration. To discover the known genetic facts about *Drosophila* has taken up the full working time of hundreds of talented researchers in many lands.

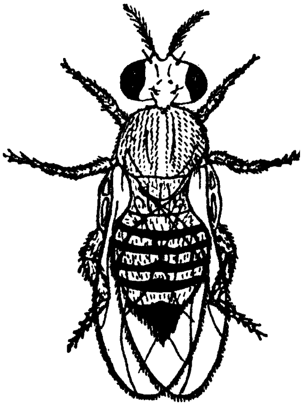


FIG. 64.—A female *Drosophila*.

With respect to hereditary make-up more is known about *Drosophila* than any other creature. Yet, as the scientists still working with that insect will agree, much more remains to be found out than has been discovered.

Of the genetics of less well studied organisms, of course, far less is known. Thus in many cases the number of linkage groups of characters so far worked out does not yet equal the known number of chromosomes. But it is significant that in no case does the number of linkage groups *exceed* the number of chromosome pairs.

About the genetic make-up of man—the number of genes, their positions on the chromosomes and the jobs they do—our knowledge is as yet only fragmentary.

What evidence is there that Mendel's laws apply to man at all?

Deliberate breeding experiments involving several generations cannot be carried out with human subjects, so most of our knowledge of human inheritance has to be derived from chance observations and family records. This is not very satisfactory but nevertheless sufficient hard evidence has accumulated to show that beyond any doubt the mechanism which governs heredity in lower organisms also operates in man. (The general understanding that family traits can miss a generation and reappear in the next is a tacit acceptance of the operation of Mendel's laws in human heredity.)

We have already seen that human eye colour is gene-controlled. Among other features known to be governed by genes are skin colour, hair colour, hair shape, baldness, type of blood group, shape of nose, head shape, height, certain abnormalities such as colour-blindness and some weaknesses which result in disease.

In a few of these cases the mechanism is known to be of the simplest type. Thus an inherited condition in which the fingers are abnormally short is controlled by a single gene known to be dominant to the gene for normal fingers. In general, however, the gene-control of human features is more complicated. Hair shape, for example, is controlled by several genes interacting in such a way as to give rise to five different types. One combination, which appears to be dominant to any other, produces woolly hair of the negro type. Another results in kinky hair which is dominant to curly—the effect of another gene combination. In turn curly hair is dominant to wavy and wavy is dominant to straight.

The most convincing evidence that human characters in general, including features like temperament and intellect, are governed by genes is provided by studies of identical twins.

As we have seen identical twins, formed by the division of a single fertilised egg, have exactly the same gene sets. If genes rather than the circumstances of later life decide a person's features then identical twins separated soon after birth should remain alike. Research has shown this to be generally true.

Identical twins, no matter what their individual circumstances of life may have been, usually have hair of the same colour and texture, similar eyes, ears and teeth and belong to the same blood group. In some cases although separated for many years and living in different countries twins have not only remained alike physically but have developed similar temperaments which they have expressed by taking up the same kind of work, marrying the same type of people and acquiring the same psychological disorders. They are often attacked by the same disease at almost the same time, exhibit astonishingly similar symptoms and commonly die within a short time of one another.

Although atoms are too small to be seen scientists have been able to find out a great deal about their structure. Is anything known about the structure of genes?

Genes are almost certainly complex protein molecules—i.e. groups of atoms of carbon, hydrogen, oxygen, nitrogen, phosphorus and sulphur. The bigger genes contain more atoms than the smaller ones; probably the average-sized gene contains about one million atoms. A chemical called nucleic acid is also present in all chromosomes and this, together with other materials, may bind the separate genes together.

Some new protein must be built up in the process whereby one gene divides to form two. Raw materials for this may be obtained from the protoplasm surrounding the nucleus. The fact that only genes can effect this synthesis of new gene-material explains why new genes, so far as is known, never arise spontaneously in the protoplasm.

We have repeatedly stressed that genes are too small to be readily seen by any methods of magnification yet developed. There are, however, certain freak chromosomes which for some unknown reason are up to a hundred times bigger than their normal counterparts and in them structures which are probably the genes themselves can be seen through a good optical microscope. These giant chromosomes are found in certain parts of the body of several kinds of flies including the geneticist's best friend, the *Drosophila* fruit fly. Fig. 65 shows part of such a chromosome found in one of the cells forming the salivary glands of a *Drosophila*. Each band probably represents a swollen gene and there is little evidence against the belief that normal *Drosophila* chromosomes are just miniatures of these giants.

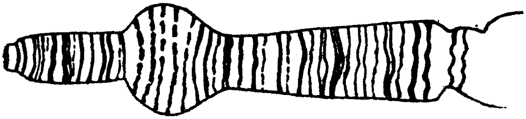


FIG. 65.—Part of a giant chromosome of *Drosophila*. The bands are believed to represent swollen genes.

A count of the total number of bands suggests that in the set of 4 *Drosophila* chromosomes there are probably about 5,000 different genes—a figure which the most up-to-date chromosome maps of this insect tend to confirm.

Is anything known about the way genes work?

The development of a fertilised egg into a complete organism takes place in a series of well-defined steps. The characters which give the organism its particular form do not all arise simultaneously but develop in a definite sequence. For example, if the fertilised egg of a certain species of fish is kept in water at a temperature of 77° F., the ears begin to develop after 33 hours' incubation, but the eyes do not begin to appear until an hour later: the heart is formed and beating 46 hours before the liver arises and so on.

This means that the genes which control the development of these separate characters jump into action in a well-defined order. Their time of action is not, however, controlled by any mechanism that could be likened to a clock. For if the egg is allowed to develop in colder water—at say 50° F.—the characters each take considerably longer to appear though they still arise in the same sequence.

Such observations have given valuable clues as to how the genes work. What probably happens is this:

Fertilisation by a sperm brings about changes in the egg's protoplasm which alter its chemical nature. This alteration stimulates certain genes in the nucleus with the result that the cell division and differentiation which constitute development begin. As one character appears further changes are wrought in the protoplasm by its appearance and these stimulate another set of genes into action so that the next character arises. This causes more changes in the protoplasm, more genes are stimulated into action and so development continues.

In the case of the fish egg which we were considering it would seem then that the protoplasmic conditions which stimulate into action the genes controlling ear formation normally arise before those which bring into play the genes controlling eye formation. It may well be, in fact, that the changes brought about in the general protoplasm of the embryo by the development of the ears directly stimulate into action the genes which cause the eyes to appear.

We can look on the protoplasm then as an immediate *environment* surrounding the genes. Changes in this environment determine the time at which different genes will react and the genes then mould the further growth of the protoplasm so that the various structures which compose the body arise. Little is known about the mechanism whereby the genes control the protoplasm but chemists are on a trail of research which is yielding some precise information in this direction.

All the essential body processes—breathing, digestion, excretion, etc.—are carried out through the agency of chemical ferments called *enzymes*. The process of development from a simple single-celled egg to a complex many-celled adult is likewise the result of enzyme activity. It has recently been shown that the production of some—and possibly of most—enzymes is supervised by genes. And in all cases so far successfully studied this relationship is as direct as it could possibly be—one enzyme being controlled by one gene.

A good example of the hereditary effect of this gene-enzyme relationship is shown by the inherited human condition called alkaptonuria. This condition does not cause ill-health. All that happens is that the affected person's urine goes very dark as soon as it is exposed to the air. Research has shown that the condition is due to the absence of an enzyme, present in the normal person's blood, which prevents the completion of a certain stage of urine formation. The condition is inherited as a recessive character on strict Mendelian lines because the absence of the enzyme is the direct result of a defect in a certain gene.

It may turn out that most of the chemical reactions making up human physiological processes are controlled by genes and that those of which man is incapable are dependent on genes not present in man's make-up. Thus the fact that man must be supplied with a constant source of vitamin C throughout life whilst the dog can make its own may be due to the absence of a particular gene which the dog possesses.

If changes in the protoplasmic environment of the nucleus can determine when *a gene will react to give rise to a character, can such changes produce any effect on* how *it will react, i.e. alter the nature of the character it produces?*

Yes. For example, if we allow our fish egg to develop in ordinary river water it will produce an embryo with two normal eyes set in the usual position, but if we add some magnesium chloride to the water, the egg will develop into a freak with a single " Cyclops " eye placed in the middle of the head. The magnesium chloride absorbed into the egg alters the chemical nature of the protoplasm and this in turn affects the expression of the genes controlling eye formation.

Again, if fertile hen eggs are subjected to abnormal temperatures during the first week of incubation the chicks which hatch from them have abnormally short backbones, whilst if young Himalayan rabbits are chilled they grow fur of a sooty colour instead of white fur.

Similar phenomena have been recorded for plants. Thus the red variety of the Chinese primrose normally breeds true to type but if its seeds are allowed to germinate at the abnormally high temperature of 95° F. they produce plants bearing white flowers.

These and other observations suggest that it will not be far from the mark to imagine the development of a character as the simple equation:

Certain genes + a certain environment = a certain character.

The equation tells us that if the genes are missing or the environment is missing the character will not appear. It also suggests that if the environment in which the genes react is slightly altered there will be a corresponding alteration in the nature of the character ultimately produced. In addition it explains why the protoplasm of the egg must be taken into account as an inherited feature affecting the expression of the genes.

It must constantly be borne in mind that by *environment* we mean in this case the state of the protoplasm surrounding the genes. In its more general use the word " environment " means the circumstances to which an organism as a whole is exposed—the climate and type of country in which it lives, the kind of food it eats, the effect of other organisms upon it, etc. Such circumstances may, of course, have some effect on the constitution of the organism's protoplasm and therefore indirectly exert an effect on the genes, but normally the protoplasm maintains a composition relatively unaffected by gross outside changes. This is especially true of warm-blooded animals where the genes are effectively buffered against the effects of outside circumstances.

This safeguard explains why a rabbit born in Australia looks in general the same as a rabbit born in England. Without it the proportion of freaks born in each generation would be so high that the species would rapidly be disorganised into extinction.

Nevertheless the Cyclops-eye fish and similar freaks show that outside environment can, in certain circumstances, exert considerable effect on how a gene will react and therefore alter the nature of the character it produces.

As one might expect the extent of the effect which the environment can exert depends on the particular genes involved. There are some genes—those controlling eye colour and finger-print pattern for instance—on which the environment appears to exert hardly any effect at all. At the other extreme there are genes like those controlling growth which respond strikingly to environmental changes. (The effect of different standards of feeding on growth rate can be seen in any big population, the better fed children being considerably taller.)

The fact that the composition of the protoplasm environment can never be *exactly* the same in any two individuals of the same species helps to explain the differences which always exist between such individuals no matter how closely related they may be.

Thus identical twins which arise by the division of a single fertilised egg have exactly the same gene constitution and to begin with the composition of their protoplasm must be the same. But as the constitution of their protoplasm begins to vary as a result of the differential action of the outside environment upon them they become recognisably different. The results of such environmental differences on identical twins are often apparent at birth, one twin being bigger than the other because it happened to get a better supply of nutriment from the mother.

The effect of environment on character was well illustrated by a recent large-scale study of identical cattle twins in which special attention was paid to body weight, size and milk yield. At the same time, however, the study showed that in general the role of heredity far outweighs the influence of environment.

Taking a broad view, then, identical twins provide striking evidence that the effects which the environment can exert on the genes are for the most part strictly limited.

When a character produced by a gene is slightly altered by the environment—as in the case of the Cyclops-eyed fish—is this alteration automatically passed on to the next generation?

The answer to this most important question is that all the worthwhile evidence so far accumulated shows that alterations of character brought about in an individual by changes in the environment are *never* passed on to the next generation.

A glance at the equation on page 118 will explain why. A change in the environment alters the way a gene expresses itself but it does not alter the gene itself. And it is the genes, not their expressions, which are passed on from generation to generation.

Changes of character brought about in a single individual by changes of environment are usually called *acquired characters*. Many scientific reports have claimed to prove that acquired characters can be inherited but not one has turned out to be correct.

The first man to put the belief forward was Lamarck, a French zoologist. He believed that if a man strengthened his arm muscles by constant exercise some degree of this extra strength would automatically be passed on to the children he might have subsequently. In this way Lamarck could explain why the sons of blacksmiths are often stronger than the sons of office workers. He could also explain certain trends in evolution which had clearly happened gradually over several generations—the gradual lengthening of the giraffe's neck, for example. Lamarck and those who followed his teaching said that modern giraffes have long necks because their ancestors had to strain their necks more and more to reach the foliage on which they fed. Each little increase in length, according to Lamarck's theory, was passed on to the next generation, which then added its increase and so on.

Now there is no doubt that by excessive stretching any individual animal can considerably increase the length of its neck in its own lifetime. The giraffe-necked women of Burma who stretch their necks from childhood by means of metal bands prove this point. But they also prove that this acquired character of being longer-necked is not inherited, for the children of the giraffe-necked women have necks of quite normal length and unless they are artificially stretched they remain normal.

Nor does it matter for how many generations such a mutilation is carried out. Thus although the Jews have practised circumcision for thousands of years their children are still normal at birth. The same applies to animals. For generations the cattlemen of the Nile Valley have trained the horns of their beasts to grow in ornamental spiral shapes without any inherited effect whatsoever. Docking the tails of sheep and horses has been carried on for hundreds of generations and still the young are born with normal tails.

It is really not to be expected that such operations would be inherited for they do not in any way affect the germ-plasm. And as we have seen it is entirely through the germ-plasm that genes and hence characters are passed on.

However, enthusiasts of Lamarck's theory have countered this objection by saying that anything that happens to the general body cells of an animal could make itself felt in the germ-plasm through the medium of the blood stream or in some other way. But again experiment denies this view.

A particularly convincing test of it was carried out with guinea pigs. In these animals black colour is dominant to white. Scientists transplanted the ovaries of a black guinea pig into a white guinea pig whose ovaries had been removed.

According to Lamarck's theory such a drastic change in environment might be expected to have some permanent effect on the black colour genes in the germ-plasm. But when this white female was mated with a white male all the offspring were perfectly black.

Similarly in experiments in which eggs were transplanted soon after fertilisation from a rabbit of one strain into a virgin rabbit of a different strain, the young to which the virgin rabbit ultimately gave birth were true genetically to the doe which had supplied the eggs and the buck which had fertilised them. The fostermother had exerted no observable effect whatsoever on their character.

To believe in the inheritance of acquired characters obviously offers a common-sense way of explaining the changes which constitute evolution. For all we need to suppose is that each slow change of climate in past ages brought about a slight but inherited change in the nature of the plants and animals alive at the time so that they gradually became adapted to the new conditions and so evolved. And just as the theory accounts simply for the development of an organ by constant use so does it explain the degeneration of an organ by constant disuse.

But as so often happens in scientific research the common-sense answer is not the correct one.

In this case we must throw Lamarck's convenient theory overboard, for its basic statement that acquired characters are inherited does not stand up to the test of controlled experiment.

If inherited changes of character cannot be brought about by changes in environment, how do they arise?

The simple equation on p. 118 again supplies the answer—if inherited changes of character cannot be brought about by changes in the environment they can only be the result of changes in the genes themselves.

If *Drosophila* fruit flies are exposed to an X-ray beam and are then allowed to breed they often produce certain offspring different in one specific feature from themselves, e.g. instead of having red eyes the variant offspring have colourless eyes or have short stubby wings instead of long wings.

If two of these flies defective for the same feature are then mated it is found that the feature is inherited in a Mendelian manner and remains fixed as a permanent character through succeeding generations.

The permanency of this effect can only mean that the X-rays have brought about a clear-cut change in the germ-plasm, apparently altering for all time the gene responsible for the character in question. (The X-rays could equally well cause permanent changes in the genes present in one of the ordinary body cells—in a cell of the skin for instance—but such changes would not be inherited for, as we have seen, only genes present in the germ-plasm, i.e. in the cells from which eggs and sperms arise, pass on to the next generation.)

What seems to happen is that the X-rays cause a minor explosion in a particular chromosome and the heat produced alters the protein molecule which forms one of the genes. It may be that its chemical nature is radically altered, new atoms being taken up into the molecule or being lost from it, but it is more likely that the existing atoms simply undergo a rearrangement to produce a gene which, because of its altered nature, behaves differently.

Such a change in a gene is called a *mutation*.

The effect of a mutation is to produce a *permanent* alteration in the character concerned, for a mutated gene thenceforth gives rise only to genes of the new type when it divides during the cell-division process. This is something quite different from the temporary modification to a character which may happen in an individual's lifetime. The first is inherited: the second is not. (The contrast is well shown by the case of the true albino girl who has white hair as a result of a mutated gene passed on to her and the platinum blonde who simply dyes her hair.)

Some mutated genes are dominant to the original genes from which they arose but the great majority of them are recessive. Of the mutations known to have occurred in the *Drosophila* fly only about 6 per cent are dominant.

Mutations can be produced by other artificial means—by exposing genes to certain gases, for instance. What is far more important from our point of view is the fact that they occur naturally.

Long before the X-ray method of producing mutations artificially was known scientists had noticed that from time to time in many widely different species of plants and animals freaks arose which, if allowed to breed, produced more freaks like themselves.

These sudden, fixed inherited changes we now know to be due to gene mutations of exactly the same nature as those produced by X-rays. It seems that every species of organism produces these mutations spontaneously from time to time, and that all the X-rays and other artificial agents do is speed up the natural mutation rate. (With a modern X-ray apparatus it is possible to accelerate the mutation rate to almost a million times the natural figure.)

Theoretically it might seem possible for a new species to arise suddenly by the gene-mutation process but this, in fact, never happens. Even closely related species differ from one another in many genes. So for a new species to arise overnight, as it were, mutations would have to occur in many genes at the same time. All the experimental evidence shows that the natural mutation rates of genes are far too slow for this to be possible.

In addition to those mutations which produce changes observable by the naked eye there are undoubtedly many more not easily recognisable because their influence is very slight or because they affect internal processes.

Convincing evidence that such inconspicuous gene-changes can have extremely important evolutionary effects has been provided by Russian research on wild dandelions.

A scientist collected from the same meadow three dandelions which were slightly different in appearance. He proved by breeding experiments that these three types each gave rise to individuals like themselves and so must be genetically different strains which had presumably arisen by mutation from some prototype. He called them strains A, B and C.

He then sowed seeds of strain A dandelions in two separate plots. In one plot the seeds were planted with plenty of distance—seven inches—between them. In the other they were crowded together at mutual distance of only one and a quarter inches.

Exactly similar double plots of strains B and C were also sown.

After two years the scientist counted the plants surviving in each plot. As would be expected he found that all the strains grew better in the less crowded plots but there was a clear-cut difference in the ability of the superficially similar strains to stand up to the rigours of overcrowding. More than 70 per cent of the A and C plants grown from seeds in the overcrowded plots had died. But of the B strain seedlings grown under identical circumstances 49 per cent had survived.

It was clear, therefore, that the gene mutations which had brought about the existence of the B strain of dandelions carried a considerable advantage in increased ability to survive the overcrowding which is so common a feature of life in the wild.

There is no knowing what mutation any dose of X-Rays will cause in a nucleus, for it is impossible to aim the rays at a particular gene. Similarly the nature of the mutations which arise spontaneously is also entirely a matter of chance.

Most mutations, whether arising naturally or artificially produced, are *disadvantageous*, i.e. those freak individuals which possess the altered gene are worse off than the normal individuals of the species. This is to be expected because any haphazard alteration in a highly complex organism is more likely to lower efficiency than to improve it. And the greater the disturbance the greater the disadvantage is likely to be, which explains why mutations producing gross changes in character rarely result in progression of the species.

The absence of horns in cattle, which, as we have seen (page 93), is caused by a gene, is a good example of a disadvantageous mutation. Cattle are normally horned, but the gene which supervises horn growth is liable to undergo one of these mutations which alters its nature. The result is that occasionally, and in a quite haphazard and unpredictable manner, a calf which never develops any horns will be born in a herd of cattle. If this calf is allowed to breed its offspring will inherit this feature, which in the wild would surely be a great disadvantage, for horns are an ox's chief defensive weapons.

On the other hand there are some gene mutations which confer advantage. For example, among herds of deer which normally bear branched antlers individuals have occasionally arisen with long straight horns. These rapier-like weapons proved much superior in the mating-season fights between the stags.

Using X-rays to produce mutations in crop-plants scientists have found that from every 8,000 seeds treated they get about 800 seedlings showing adverse inherited changes and one seedling which appears to be an improvement. Since X-rays apparently just speed up the mutation rate without affecting the type of mutation produced, this proportion of 800 : 1 probably holds in nature.

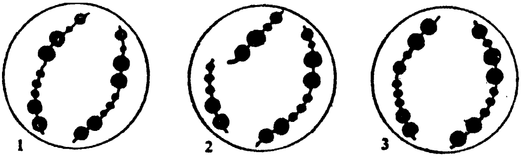


FIG. 66.—The recombination of genes following breakage of a chromosome. The top segment of the broken chromosome turns round before rejoining.

Bombardment with X-rays has another effect on the chromosomes besides causing individual genes to mutate. It sometimes causes a chromosome to break into two or three pieces. If these bits rejoin in their original positions the ultimate effect of the breakage is nil, but if they unite in a different order as shown in Fig. 66 character changes arise which are sometimes sufficiently distinct to be obvious to the naked eye. And since such chromosomal changes are permanent their effects are *inherited.*

It seems that a reshuffle of the complex of genes which does nothing more than alter their relative positions on the chromosomes can result in changes which are inherited.

Thus it has been shown that when two particular genes happen to be carried on the same chromosomes in the *Drosophila* fruit fly the insect's eyes are smaller than when these genes are on separate chromosomes.

There is a simple explanation of this rather remarkable fact. It is that the immediate environment of any one gene is made up not only of the surrounding protoplasm but includes the other nearby genes as well. An alteration of the pattern in which these genes are arranged therefore changes the internal environment permanently and inherited variations of character are the result.

The importance of all this from the point of view of evolution lies in the fact that gene recombinations following chromosome breakages occur spontaneously in nature. As in the case of gene mutations their occurrence is quite sporadic and their effects are fortuitous and unpredictable.

Another way in which new combinations of genes—and hence inherited character changes—arise naturally is through the process of crossing-over—the exchange between chromosomes, which as we have seen (page 112) takes place at egg and sperm formation.

Finally a gene complex may become permanently altered as a result of a failure in the chromosome mechanism whereby a cell normally divides so that an organism arises with twice the normal number of chromosomes—say 24 pairs instead of 12 pairs. Such organisms are particularly common in the plant world and they are usually quite different from the normal types from which they accidentally sprang. Often they are giants with increased resistance to disease and this gives them special value to agriculture and horticulture. Some of them are better fitted to withstand rigorous climatic conditions than are the normal forms. In Britain the common valerian does not occur further north than the Midlands, whilst a variety of it with double the usual number of chromosomes extends to the north of Scotland.

Cultivated wheats, roses, chrysanthemums, blackberries, loganberries and pears are among the many economically important plants with more chromosome sets than their wild ancestors.

Methods of inducing this doubling-up of the chromosomes artificially have been devised. Thus by treating parts of a plant with a chemical called colchicine giant varieties of wallflowers and phlox have been produced.

It has been stressed that new species cannot arise by simultaneous mutations in several genes resulting in drastic changes between one generation and the next. That is true, but the chromosome doubling-up process sometimes results in immediate and permanent changes so pronounced that the freak offspring have to be classed as distinct varieties, and, in special cases, as distinct species. The history of the commonly cultivated *Primulas* provides excellent examples of both kinds of change.

Several times peculiar giant plants have developed from what were believed to be normal Chinese primrose (*Primula sinensis*) seeds but later proved to have 48 pairs of chromosomes instead of the customary 24 pairs. The giant variety was not only bigger in overall size but its individual cells and pollen grains were bigger. When self-pollinated it bred true to type and crossed with the normal form only with great difficulty.

On another occasion two different species of *Primula* were crossed at Kew Gardens. Instead of the expected sterile hybrid with 9 pairs of chromosomes, a giant plant with 18 chromosome pairs and which proved to be quite fertile was obtained. This plant, which bred true to type, was so different from either parent that it had to be classed as a new species—*Primula kewensis.*

This new species was, of course, the result of artificial breeding under special conditions of cultivation, but there is strong evidence that such new species do occasionally arise by the same process of crossing and chromosome doubling in the wild. It certainly seems to have been the mode of origin of the common hempnettle, *Galeopsis Tetrahit.*

This cornfield weed has two close relatives, the large-flowered hempnettle, *Galeopsis speciosa,* and the hairy hempnettle, *Galeopsis pubescens,* each of which has 8 pairs of chromosomes. When these two species were crossed in a breeding experiment some accident of cell division occurred and the resulting hybrid had 12 pairs of chromosomes instead of 8. The hybrid was then fertilised with pollen from a hairy hempnettle and the result was a further freak with 16 chromosome pairs. This freak looked exactly like a common hempnettle and the likelihood that the wild *Galeopsis Tetrahit* originated in this way is heightened by the fact that it always has 16 pairs of chromosomes.

There are very few cases where a wild plant has been "re-created" like this, but the chromosome numbers of related species strongly suggest that chromosome doubling probably coupled with crossing has been an important factor in the evolution of many plants. Thus among chrysanthemums there are several species with 9 pairs of chromosomes each, one with 18 pairs, one with 27 pairs, one with 36 pairs, and one with 45 pairs: among roses there are species with 7, 14, 21 and 42 chromosome pairs and so on. Of the native flowering plants in Britain something like 45 per cent have probably arisen by the chromosome doubling-up process. In Spitzbergen the proportion is believed to be as high as 80 per cent, the accidental doubling of chromosomes being apparently more common in cold climates.

The doubling-up of chromosomes has been noted in several invertebrates, but it seems always to have been a rare occurrence among animals and has not been an important factor in their evolution.

Does a mutation in one gene affect the other genes in the cell?

Not directly. Mutations occur in one gene at a time, in one cell at a time. Only the gene concerned is altered structurally. Thus if a mutation occurred in the *B* gene in the ovary cell shown in Fig. 61 it would not alter in any way the structure of the *b* gene on the corresponding chromosome. Therefore when these two chromosomes separated at egg-formation the eggs containing the mutated *B* gene might develop into a rabbit with freak coloration but the eggs containing the *b* gene would be quite normal.

A mutation in one gene must, however, have an *indirect* effect on the other genes in the nucleus for it represents a permanent alteration in their immediate environment. Therefore in the case we have been considering a mutation in the *B* gene would probably always have some effect on the expression of the *T* gene in the same chromosome and this effect would, of course, be inherited.

How strong such secondary effects of a mutation can be is shown by certain sheep which though carrying a double dose of the gene for horn production are nevertheless without any trace of horns owing to the presence of a quite different mutated gene whose influence entirely suppresses the action of the other two.

Generally, however, the secondary effects of mutations are too slight to be easily observable. This does not mean they are not important. On the contrary it is the slight changes in an animal's make-up which play the most important part in evolution.

From the evolutionary point of view, then, a mutation is best regarded not simply as a straightforward change in the structure of one gene but as a sudden alteration of the gene-complex as a whole. The result, as a rule, is not only an observable change in one specific character but a subtle and far-reaching change in the whole organism.

Do mutations and gene recombinations occur in human beings?

There is no doubt that gene recombinations as a result of crossing over and chromosome breakage occur regularly in human beings with important inherited results. It seems likely, for instance, that the sudden appearance of a genius in a quite ordinary family is the result of a particularly favourable chance combination of genes.

There is plenty of evidence that straightforward gene mutations also occur.

Of these the best known is the one giving rise to hæmophilia, a condition which reduces the clotting power of the blood and renders the affected person liable to severe hæmorrhage from a slight cut. The mode of inheritance of hæmophilia has been especially well studied because of its occurrence in several royal lines. The Spanish Hapsburgs, the Romanoffs and several prominent European families all carried a mutated gene causing hæmophilia which showed up—sometimes with important historic consequences—in the male issue. (For a reason which will be explained shortly the hæmophilia gene most commonly produces its unfortunate effect in males but females can act as carriers and pass the gene on to their male offspring.)

Now as Table 5 shows, the "royal" hæmophilia gene is traceable in every case to the British Queen Victoria. And as she had no ancestors with abnormal blood the mutation of the normal gene into the gene causing hæmophilia must have happened in one of her parents or in her own germ-plasm during her embryonic development.

The result of this accidental gene change has been that ten of Queen Victoria's male descendants have suffered from hæmophilia and at least seven of her female descendants have been carriers. (Through the Queen's two daughters, Victoria and Alice, the gene went into the royal lines of Germany and Prussia. Through Alice's daughter who became the Czarina of Russia it showed up dramatically in the Czarevitch Alexei. Via Queen Victoria's youngest daughter, Beatrice, the gene went into the Spanish royal family showing up in both sons of Alfonso VIII. Victoria's son Leopold, was himself hæmophilic. Edward VII, from whom the reigning British Royal Family is descended, fortunately escaped the gene as a result of the random separating out of interchangeable gene-pairs at egg-formation.)

Among other unpleasant conditions believed to be due to gene mutations are colour-blindness, hereditary deaf-mutism and Friedreich's ataxia which behave as recessives, and mongolian idiocy, Huntington's chorea and an hereditary form of jaundice which behave as dominants.

Because the human gene-complex is so intricate and delicately balanced, mutations and chromosome breakages are far more likely to produce adverse effects than to bring about improvements. No doubt many human gene changes are advantageous, but these will most commonly be found among the relatively slight alterations which cause character changes too small to be immediately noticeable.

Can a mutation be so disadvantageous that it kills the organism in which it appears?

Yes. Since, as we have seen, genes seem to control the chemical processes which cause the egg to develop and enable the adult organism to breathe and feed we should expect that sudden changes in their structure might at times prove fatal. This is the case. Many so-called *lethal* mutations which bring about the death of the organisms carrying the affected genes are known.

Such a mutation may bring about its lethal effect almost immediately by preventing a fertilised egg from beginning development or even by killing an egg before it can be fertilised —as is known to happen in certain plant mutations.

On the other hand it may not kill until quite late in development. Many human miscarriages may represent lethal mutations which come into action fairly late in embryonic growth.

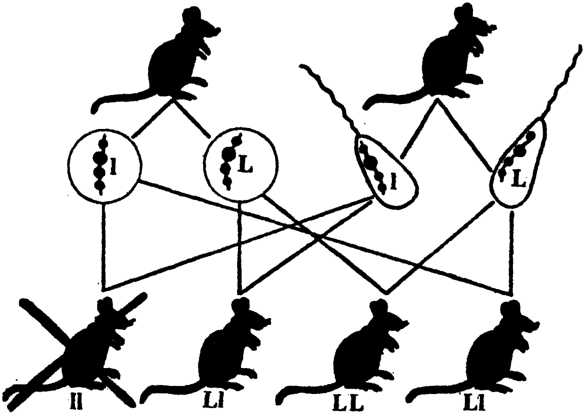


FIG. 67.—The effects of a lethal gene in mice. The recessive *l* gene arose as a mutation from the normal gene *L*.

Some lethal genes are known which are dominant and therefore can never be passed on from one generation to another because they always kill before the organism carrying them has time to reproduce. But many lethal mutations are recessive to their normal counterparts and can produce their effect only when the dominant normal is absent, i.e. when they are present in the double dose.

Fig. 67 explains a case of this kind found in a certain variety of mice.

Yellow mice carry a normal gene *L* on one chromosome and a recessive lethal gene *l* on another. When two of these mice are crossed about 25 per cent of the embryos in the resulting litters die in the womb. These are the embryos which had the misfortune to develop from fertilised eggs containing two *l* genes. In a similar manner chicks carrying a double dose of a certain recessive lethal gene die in the shell.

Quite often animals afflicted with lethal genes are born alive but die within a few hours or days. Thus there is a gene present in the Dexter breeds of cattle which causes the calves bearing it in the double dose to die from paralysis of the breathing organs. In certain strains of Percheron horses some of the foals are born with a permanently closed food canal. Due to the action of other recessive genes pigs may be born with no legs—a deficiency which spells certain death since an affected piglet cannot reach its mother to suckle—and so on.

Lethal mutations are also known in plants. There is a recessive gene in Chinese primroses which in some way interferes with the formation of chlorophyll. In the single dose the gene causes the plant to be yellow instead of green. In the double dose it completely suppresses chlorophyll development and an affected seedling, which is practically white, always dies.

There are a few known genes which are not lethal in the sense that they kill the individual, but are lethal from the point of view of the species as they prevent the individual from breeding.

Such a gene was found among certain offspring of a variety of tame mice. These mice stopped growing when they were only a fortnight old because the gene caused a defect of a gland which controls growth. In addition to being dwarfs the mice were also quite sterile.

The results of a chromosome breakage may also be lethal because the pieces sometimes fail to rejoin and get lost at cell division. Perhaps too in some cases where rejoining does occur the genes are reshuffled to a degree which proves too drastic for the affected egg to complete development.

Does a recessive lethal gene produce no effect at all when it is present only in the single dose?

In the yellow mouse case we have just considered, the recessive lethal gene does appear to be completely dominated by the normal gene. Mice which carry both these genes are therefore just as likely to survive as are completely normal mice which do not carry the lethal gene at all.

In the past this behaviour was thought to apply to recessive lethal genes in general, but recent and more critical research has shown that some of them are not entirely inactivated by the presence of the corresponding dominant genes : their effect is swamped but not completely suppressed. Thus it has been proved that fertilised *Drosophila* eggs which carry one recessive lethal gene and one normal gene are slightly less likely to develop into mature flies than are eggs carrying only normal genes.

This is perhaps just what we should expect when we remember that all the genes in a nucleus are intricately integrated to form a complex behaving largely as a single unit. It may well turn out, in fact, that all recessive genes whether lethal or not exert some effect when present in the single dose. Should this prove true it will have to be taken into account as one of the most important factors in evolution, for it will mean that a new recessive gene produced by mutation can exert some degree of influence immediately instead of having to wait until it chances to meet up with a gene like itself.

A simple example will make this point clear. Suppose we have a plant in which resistance to a certain disease is governed by a gene called *R*. The germ-plasm cells of this plant—whether male or female—contain two chromosomes which each carry the gene *R*. Now suppose that during the formation of an egg-cell in one of these plants a mutation of one of the *R* genes occurs resulting in a new recessive gene, *r*, which confers increased resistance to the disease in question. Before it can develop further the egg containing the new *r* gene has to be fertilised by a pollen grain. All normal pollen grains, however, contain the dominant gene *R*, so that if *r* is completely recessive it can have no effect whatsoever on the egg in which it arises, being entirely suppressed by *R*. The *r* gene can express itself only when the egg containing it is fertilised by a pollen grain which also contains *r*. If, on the other hand, the gene *r* can exert even only a slight degree of influence in the presence of *R*, the new *Rr* type egg will develop into a plant a little better equipped to escape disease than the normal *RR* specimens.

The fact that a recessive gene-mutation produces only a slight effect or no effect at all when it first occurs raises a difficulty for the practical scientist. To interpret his results properly he needs to know whether a recessive character that suddenly appears in his breeding stock is the result of a new mutation or the expression of recessive genes which have been carried in the dormant state for several generations. The only way he can get over this difficulty is by carefully tracing the ancestry of his experimental stock when this is possible and by carrying out test matings to bring hidden recessives to light before he begins his real experiments.

The ideal material for such experiments is a collection of organisms in which the individuals are identical as far as their inherited quotas of genes are concerned. Such a collection is called a *pure line.* Noticeable differences do arise between the individual of a pure line but, except where mutation has occurred, these are always due to the various influences of environment and are not inherited.

It is, in fact, from the study of pure lines that some of the strongest evidence against the theory that the effects of environment can be inherited has been derived. Thus it was found that although the seeds in a pure line of bean plants varied in weight from 9 grains to 20 grains—owing to the fact that some had received more sap than others during their development—there were no inherited differences between the plants grown from these seeds. The average weight of the beans on a plant grown from a 9-grain seed was as high as the average weight of those borne by a plant grown from a 20-grain seed. And the numbers of very small and very large seeds produced by the two types of plants were about the same.

It will be obvious, therefore, that within a pure line it is impossible to alter a character by selecting particular individuals and breeding from them. In the case of the beans, for example, it would not be possible to increase the average weight of the seeds by continually selecting the big ones and growing only from them. Any inherited changes which arise within a pure line must be the result of mutation.

When a great number of genes are involved, as is the case with most organisms used in breeding experiments, it is not possible to develop absolutely pure lines. But experimenters can ensure that their stock is reasonably pure for the particular genes they wish to study. Research results have sometimes been completely invalidated by failure to take this precaution.

Now there is one type of recessive gene mutation which can exert its full effect from the moment it arises—the type known as a *sex-linked* mutation. To understand it some knowledge of the mechanism which determines sex is essential.

The body cells of a female *Drosophila* fly each have the four chromosome pairs shown in Fig. 68. The members of one particular pair are called X chromosomes and, as is usual with chromosome pairs, they are alike in shape, length and gene-content. The two corresponding chromosomes in the male *Drosophila*, however, are not alike. One, called the X chromosome, is identical with the X chromosomes of the female but the other, called the Y chromosome, is of quite different shape and length and lacks many of the genes carried by the X chromosome.

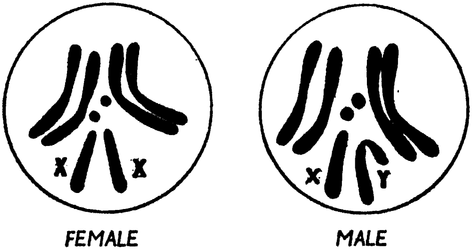


FIG. 68.—Body cells of female and male *Drosophila* flies showing the sex chromosomes.

Because the members of each chromosome pair separate at germ-cell formation every egg gets an X chromosome but 50 per cent of the sperms are without one and carry the Y chromosome instead. Fig. 69 shows what happens at fertilisation as a result of the existence of these two types of sperms. Two sorts of fertilised eggs arise—one carrying two X chromosomes, the other carrying one X and one Y. *The XX eggs always develop into female flies: the XY eggs always develop into males.*

Now let us examine the effects of this sex-determining mechanism on certain recessive mutations.

We have seen that each X chromosome carries certain genes which are not present in the Y chromosome. Suppose that a mutation occurs in one of these genes to produce a new gene which is recessive to the old one and that the X chromosome concerned is located in one of the germ-plasm cells of a female *Drosophila*. Eventually this chromosome with its mutated gene will get into an egg, but if this egg is fertilised by a sperm carrying an X chromosome the mutation will not show up in the female fly resulting from the union, for the X chromosome of the sperm will carry the old-type gene which is dominant to the mutated gene. If, on the other hand the egg is fertilised by a sperm carrying a Y chromosome there will be no old-type gene to suppress the action of the mutated gene and the male fly resulting from the union will develop the new character, although the gene responsible for it is really recessive and present only in the single dose.

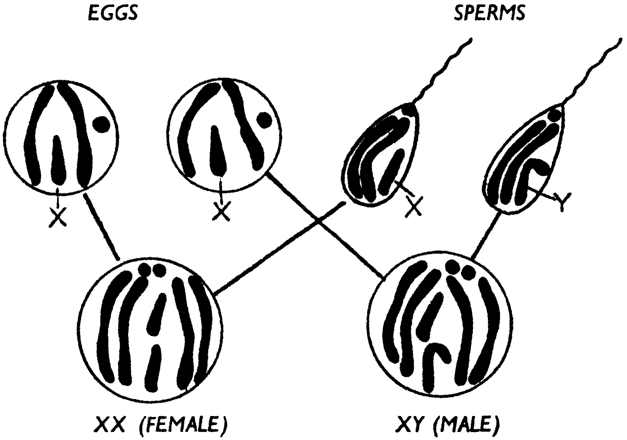


FIG. 69.—How sex is determined in *Drosophila*.

This phenomenon whereby the sex-chromosome mechanism causes a character to appear in one sex and to lie dormant in the other is called *sex-linkage*. It is put to good use by poultry breeders who exploit it to distinguish between the sexes of day-old chicks.

Newly hatched male and female chicks are normally indistinguishable except to the expert trained to detect minute differences between the sex organs. But by crossing certain breeds, e.g. the Light Sussex and Rhode Island Red, in a particular manner it is easy to detect sex at hatching because the young cockerels are covered with down of one colour—say reddish—whilst the pullets have the more usual yellow colour.

This colour difference between the sexes is due to the fact that those eggs carrying two X chromosomes contain a dominant colour gene which is absent from the eggs carrying only one X chromosome.

We have already dealt with a clear-cut example of sex-linkage in human heredity—the case of the inheritance of hæmophilia. The mutated gene carried by Queen Victoria was located on one of the X chromosomes in each cell of her germ-plasm. Its effect did not show up in her because the dominant normal gene was always present in the other X chromosome. For the same reason it did not appear in her three daughters although they all had the misfortune to arise from eggs containing the defective X chromosome and were therefore hæmophilia carriers. Prince Leopold, who also inherited the defective X chromosome from his mother, actually suffered from hæmophilia. Developing from an XY type of egg he had no additional X chromosome carrying a normal gene to suppress the action of the dangerous mutation. King Edward VII was just lucky that the egg from which he arose happened to contain the normal member of Queen Victoria's X chromosome pair.

In this light it is easy to understand why hæmophilia is rare in women. A female will show it only when both X chromosomes in the egg from which she develops carry the mutated gene. Such an unfortunate combination could be the result of a separate mutation in each X chromosome, but is more likely to arise from the chance union of a hæmophilic man and a " carrier " woman.

Do mutations occur only in the cells of the germ-plasm?

No. They occur probably just as frequently in the ordinary body cells. Such *somatic* mutations, as they are called are, of course, never passed on to the next generation being acquired characters which do not affect the germ-plasm.

White patches which are sometimes present in the red eyes of *Drosophila* flies and are not hereditary are believed to be the result of somatic mutations. So are certain cancerous growths. (All malignant growths brought about by exposure to X-rays or atomic radiation are believed by some authorities to be due to induced mutations in the genes of the cells concerned.)

The circumstances as regards somatic mutations in plants are different, for there is no clear-cut distinction between germ-plasm and body cells in the plant world. A mutation in the growing point of a young twig may lead to the appearance of a freak branch on an otherwise normal tree, and since the egg cells and pollen grains as well as the general tissues may arise from the growing point, such a gene change can be inheritable. Thus the weeping willow which arose as a mutation from an ordinary willow tree in China bears seeds which —if fertilised by pollen of the same type—give rise to trees with the weeping habit.

Somatic mutations in plants which do not affect the reproductive organs—those occurring in the roots, for instance— are never inherited.

Permanent changes in plant characters resulting from a doubling-up of the entire chromosome set due to a fault in the cell-division process are sometimes inherited. There is a giant form of the Chinese primrose, for example, which arose in this way and can be propagated by seeds in the normal manner.

Quite often, however, freaks with extra chromosome sets prove to be sterile and can be propagated only by means of cuttings.

Apparently not only can gene mutations occur in any cell but they can take place at any time, i.e. their occurrence does not seem to be restricted to any particular stage of cell division.

What causes natural gene mutations?

Following the discovery that X-rays and ultra-violet light could produce gene changes it was suggested that natural mutations were due to naturally occurring rays, in particular to cosmic rays—a penetrating form of energy reaching the earth from an unknown source. This was thought to be especially likely as the mutations produced by X-rays were the same as those occurring naturally, the artificial radiation merely speeding up the normal mutation rate.

Drosophila flies were therefore sent up in balloons to the stratosphere where the strength of cosmic rays is greater than at sea-level. At a height of 13 miles the mutation rate was increased fivefold.

It has since been generally agreed, however, that the normal strength of naturally occurring radiations is much too low to account for anything like the total number of natural mutations.

All that we know with certainty about the occurrence of natural mutations is that at some unpredictable moment any gene is likely to undergo a sudden permanent change which causes a permanent alteration in the character with which that gene is concerned.

Every plant and animal so far bred in large numbers in scientific experiments has produced mutations.

The *Drosophila* fly—the most closely studied single organism—has produced well over 1,000 different mutations in the last 40 years.

Can the same mutation occur more than once?

Yes, quite definitely. The mutation which produces hornlessness in cattle has arisen independently in several breeds so that breeders have been able to establish polled strains of Shorthorns, Friesians and Herefords, which are normally horned. At the time of writing the same mutation has just been reported for the first time in a Guernsey bull. Perhaps some day there will be no horned breeds of cattle for the polled types are easier to manage and do not injure one another so frequently.

In 1791 a peculiar ram with very short legs arose from a normal flock of sheep in America. Because it could not run very quickly and was therefore easy to catch it was used for breeding and its peculiar character was found to be the result of a gene mutation dominant to the normal type. By crossing the ram with some of its offspring a pure breed of so-called Ancon sheep was established. It did not prove popular, however, because the short-legged sheep were difficult to drive to market and the breed died out completely. Exactly the same mutation arose in Norway in 1925 and again a breeding flock was established from it.

Another mutation in sheep which causes the affected animals to develop without any external ears has also arisen separately —in Russia and in the U.S.A.

Among human mutations hæmophilia, albinism and colour-blindness have doubtlessly arisen many times quite independently. It seems in fact that every gene mutates with a specific frequency which can be calculated statistically.

Thus it has been worked out that an advantageous mutation might be expected to occur in one out of every thousand million people born. Looked at with the human life-span as a time-scale this frequency seems very low indeed. But set against the background of geological time it has considerable significance.

Does the fact that genes can mutate explain the existence of the pairs of interchangeable characters of the type studied by Mendel?

Yes. Horn production in cattle, for instance, must originally have been controlled by a single gene which eventually mutated in some individuals to give rise to the new gene causing horn suppression. Thenceforth these two genes formed an interchangeable pair. In the case of the Andalusian fowls the birds may all have originally been black, a mutation in the gene controlling colour having brought about the existence of a white variety. In our examination of the inheritance of hæmophilia we have seen a human case where an interchangeable pair of genes has arisen as a result of mutation in a single original gene.

There is, of course, no theoretical reason why a gene should mutate in only one way. Two original-type genes may undergo different molecular changes giving rise to two quite distinct mutations which, together with the parent gene, make up an interchangeable triplet. Thus a new mutation in the gene controlling pigment production in Andalusian fowls might give rise to red feathers instead of black and then we should have three interchangeable colour genes instead of only two. Or the mutated gene of an interchangeable pair might undergo a further mutation in certain individuals giving rise to a third gene in this way.

Cases of this sort where several different mutated forms of a gene exist in a species giving rise to several variations of a particular character are common. Thus comb shape in fowls is determined by three interchangeable genes—the two we have already mentioned which produce single and rose combs respectively, and a third producing a comb of different shape styled pea comb. The colour of the coat in rabbits is controlled by four interchangeable genes each giving a different fur colour.

Hair shape, eye colour, skin-colour and blood-group type are among the many human characters each controlled by several interchangeable genes.

The record appears to be held by the gene which controls eye colour in the *Drosophila* fly. The normal form of the gene produces red eyes but it has mutated in thirteen different ways each giving rise to a different eye colour in the individual carrying it.

Can a gene which has mutated mutate back to its original form?

Yes. This has proved to be possible in experiments with X-rays and there is little doubt that it happens occasionally in nature.

When animals and plants bred under artificial conditions have been turned loose and forced to live under natural circumstances they have usually reverted within a few generations to a form very close to that of their wild relatives. Fancy breeds of goldfish and high-yielding varieties of cereals are good examples of organisms which behave this way.

In part the reversion is due to the changed reactions of the genes in the different environment but it is largely the result of reverse mutations.

This suggests that by a series of reverse mutations any animal could change back to an ancestral form. Such a wholesale reversion never happens in nature for the likelihood that just the right collection of back-mutated genes will turn up in a single individual is too small, but it can be brought about artificially. By selecting individual reverse mutations and combining them in one animal by a long and carefully planned breeding programme it is possible to get very near to re-creating an ancestral type provided the breeder knows exactly what this type looked like.

This interesting process has been used to re-create the aurochs—the original wild ox of Europe from which our domestic cattle are derived. The aurochs became extinct early in the seventeenth century but from paintings and descriptions a fair picture of what the beast looked like is available. Using Hungarian cattle as the starting-point breeders have gradually selected the various characters of the aurochs as they chanced to appear in odd individuals and have blended them to produce animals very like the extinct beast. Other breeders have achieved equally effective reconstructions by using Spanish fighting bulls as raw material.

It must not be thought from all this that it is very easy for a gene to mutate. If this were the case the differences between individuals of the same species—men for example—would be much greater than they are and the species would be continually undergoing rapid changes.

The true position is that genes as a whole are remarkably constant in their nature but every now and again an odd one undergoes a mutation which may prove to be temporary but is far more likely to remain permanent. It is largely through a succession of such mutations that each living organism has evolved.

New combinations of genes can also, in theory, revert to their original arrangement by an exact reversal of the chromosome breakages and crossings-over which brought them about, but when large numbers of chromosomes and genes are involved this is most unlikely to happen in practice.

SECTION III

EVOLUTION IN ACTION—THE INTERPLAY OF HEREDITY AND ENVIRONMENT

If advantageous changes in the gene complex are not so common, how is it that domestic animals such as the dairy cow, sheep and pig have altered so much within the last 200 years?

The answer is that nearly all the changes brought about in animals by domestication would be disadvantageous in natural circumstances.

It is no advantage to a cow, for instance, to produce more milk than is needed to feed her calves. The huge udder and excessively long period of lactation which characterise the modern dairy cow would be decided disadvantages in the wild. So too would be the great muscle development of the Shire horse, which would greatly reduce the animal's speed of escape whilst not improving its power of self-defence against a determined carnivorous beast.

From the point of view of the natural evolution of species it is difficult to think of any advantageous character which has been conferred by domestication. Even the general increase in fertility shown by the pig would almost certainly be a drawback in the wild, for a sow would be hard put to find enough nutriment to suckle more than the natural number of four piglets. And in any case this fertility increase is outweighed by an overall reduction in hardiness and resistance to disease.

This general contention is upheld by the way animals and plants whose constitution has been altered by man revert to the wild condition when forced to live under natural circumstances. It has been well shown by domestic pigs turned loose in New Zealand. There were no wild pigs there for them to breed with but after a few generations they took on the physical characters and behaviour of the wild pigs from which they were originally descended.

(Since the stockbreeder is now a dominating influence in the environment of domestic animals it can reasonably be argued that any mutation which pleases him is a genuine advantage to them from the evolutionary standpoint for it helps to ensure the continuation of the species. Man's influence, of course, must be regarded as an increasingly important environmental factor in the lives of practically every organism, but as it covers only a minute period of the earth's history it is best regarded as an artificial factor in a general study of evolution.)

Another reason why the changes in the nature of domestic animals have been so rapid is that man has consistently *selected* for further breeding those beasts which, as a result of alterations in the gene complex, were improvements from the agricultural standpoint. In this way mutations and other gene changes rated by breeders as desirable were conserved whilst the more natural types gradually died out.

Different gene combinations were selected for different purposes with the result that we now have some breeds of cattle genetically equipped to yield excellent beef whilst others are genetically specialised to yield large quantities of high-quality milk. In the same way we got racehorses and draught horses, the wool and mutton types of sheep and the many breeds of dogs.

Dogs especially show the remarkable scope of variety which can be achieved within a single species by selection of particular gene combinations and mutations. There are well over one hundred clear-cut breeds of dogs ranging in size and form from the 200-lb. Great Dane to the 2-lb. Chihuahua and all undoubtedly belonging to one species—*Canis familiaris*—which seems to be descended from the wild Northern wolf.

Two additional factors have increased the rapidity with which man has been able to bring about fixed changes in domestic animals by selection :

(1) Under the especially favourable conditions of the stockbreeder's establishment animals showing the effects of gross mutations, which would have brought about their death at an early age, have been able to survive and pass on their mutated genes.

(2) By a deliberate process of *close inbreeding* stockbreeders have been able to make immediate use of mutations to a

degree which could never have been achieved in the wild or would have taken thousands of generations to establish.

What is meant by close inbreeding?

Close inbreeding implies the mating of animals which are very nearly related, e.g. the mating of sire to daughter, dam to son and brother to sister.

It is easy to see why this practice leads to the rapid establishment of new mutations. Let us suppose that in a herd of beef cattle a heifer calf is born with a new and especially desirable feature due to a new dominant gene called *D* which has arisen by mutation from the normal gene *d*. The ovary cells of this heifer will each contain one chromosome bearing the new gene and one chromosome bearing the old gene, so that two types of eggs will be produced—one carrying the *D* gene, the other carrying *d*. To mate this heifer a bull of the normal type carrying a double dose of the *d* gene and producing only *d*-carrying sperms will have to be used. By the laws of chance therefore 50 per cent of the calves resulting from the union will contain *D* and *d*, and so show the new character, whilst the other 50 per cent, carrying only *d* genes, will be normal. If we continued to use other old-type bulls to mate with these *Dd*-type offspring we should never produce any calves pure for the new character, i.e. each containing two *D* genes, and 50 per cent of our new stock would always be of the normal type.

Now suppose, on the other hand, that we take the first *Dd*-type bull calf produced by our original heifer and mate it with its mother. Then not only do we reduce the likelihood of getting calves lacking the desirable gene from 50 per cent to 25 per cent, but we give ourselves a 25 per cent chance of getting calves pure for *D*. By pursuing this inbreeding process and mating the first *DD* bull that arises with the first *DD* heifer calf we can establish within a few generations a strain of cattle which, since they contain no *d* genes, will produce 100 per cent of calves with the new feature. For this to happen as a result of the random matings which take place in a badly managed or wild herd may take hundreds of generations.

An inbreeding policy carries another great advantage in that it shows up desirable recessive mutations which might never be noticed otherwise or would certainly not appear for a long time.

To illustrate this important point let us suppose that a new recessive gene, *b*, which could produce a desirable character has arisen in a heifer calf by a mutation of the normal dominant gene *B*. It will not show up in the heifer because only one of the *B* genes she would normally carry in every cell has been changed into a *b* gene and the remaining *B* gene is dominant. A normal *BB*-type bull has to be used to mate this heifer and therefore none of the first generation calves can show the new feature, though 50 per cent of them can be expected to carry the new gene. If, however, a policy of close inbreeding is being pursued and one of the *Bb*-type bull calves is mated back with its mother there is immediately a 25 per cent chance that calves carrying a double dose of the recessive gene and, therefore, showing the character will be born. Once the new character is spotted a strain of cattle guaranteed to produce calves showing it can be established by further breeding from males and females each showing the character and therefore pure for the *b* gene.

With the random matings which occur in the wild thousands of generations would be required for the establishment of such a gene.

Doesn't such close inbreeding lead to a rapid weakening of the stock?

Not if the stockbreeder carries out a policy of ruthless selection keeping only the best animals for breeding and discarding the worst.

We have seen that inbreeding brings to light useful recessive genes which would otherwise remain dormant. In the same way it quickly shows up undesirable recessives.

If there are any bad recessive genes in a herd or family close inbreeding gives them a good chance to combine in the double dose, and weaklings, freaks and mental defectives are the result. The intelligent breeder automatically discards such abnormalities and so gradually weeds out the undesirable recessives from his stock. Once the bad genes have gone further inbreeding does no harm at all. In fact when a stock comes to contain a preponderance of desirable genes inbreeding is the best way of ensuring that they remain desirable.

For practical proof of the value of inbreeding one has only to examine the history of the British breeds of farm animals. The pedigree of the famous bull Comet—called the father of the Shorthorn breed—shows an astonishing degree of inbreeding. A cow called Phœnix was mated with its step-brother and produced a bull called Favourite. Phœnix was then mated with Favourite, her own son, and produced a heifer called Young Phœnix. When mature the heifer was mated with her father Favourite and the bull, Comet, was the result. Favourite was thus both the father and the grandfather of Comet, whilst Phœnix was its grandmother on both sides of the house.

In developing the Aberdeen Angus breed of cattle close inbreeding was practised for fifty years, the stock bull being regularly succeeded by one of its own sons. In improving the Leicester breed of sheep the highest degree of inbreeding was used.

Provided that the male and female are anatomically sound sperms will fertilise eggs regardless of the closeness of relationship. And if these germ-cells do not carry lethal genes the fertilised eggs will develop in the normal way.

In most modern societies there are legal objections to the close inbreeding of human beings. These objections are based on the humanitarian principle that it is not practicable to eliminate the freaks which are likely to arise from the marriage of very near relatives as a result of the combination of recessive genes.

The psychological distaste for incest is undoubtedly acquired during the life of each individual and is not an inherited pattern of behaviour. That it need not necessarily be harmful is shown by the history of ancient Egyptian royalty who were not allowed to marry outside their own families. Cleopatra, for example, married her younger brother Ptolemy.

Among many wild herd animals close inbreeding involving repeated father and daughter matings is practised almost exclusively. The importance of this fact in the great struggle for existence on which evolution depends will be discussed later.

Exactly what is meant by " the struggle for existence " ?

It is the continual competition which goes on between organisms as a result of their individual urges to survive and procreate themselves.

Perhaps its most obvious expression is the incessant struggle between herbivorous animals, typified by the zebra, and the carnivores which prey on them. More often than not it is the individual of least immediate value to the herd—the lame or half-blind zebra—which is killed off by the lion. By continually weeding out individuals weakened by accident and disease lions ensure that the quality of a zebra herd does not deteriorate. And since they also tend to eliminate individuals weakened by adverse gene changes they ensure that the quality of the zebra species does not decline.

In point of fact they do much more than this for the species. Since the value of an advantageous gene change is enhanced by the ruthless struggle, the carnivorous beast by its constant attentions actually speeds up the evolution of its prey.

Automatically any important alteration in the nature of the prey has a recoil effect on the evolution of the predator. If the zebra becomes harder to catch lions showing an improvement in speed of attack will be more likely to survive than slow ones and so reproduce more lions like themselves.

This flux of change and counterchange occurs between competing organisms from the largest to the most minute. In the last few years we have seen man improve his ability to survive the struggle for existence by developing new drugs—the sulphonamides—which are death to previously unconquerable germs. And we have seen how the germs reacted to this sudden shift in the balance of nature by arising in new strains resistant to the drugs. These strains arose by chance mutations which happened to be better fitted than the old form to survive in the altered struggle.

In ways more subtle than the obvious clash of adaptations for attack and defence, but no less ruthless, organisms constantly compete for limited food supplies and living space.

What seems to be the closing phase of just such a struggle is now being fought in the Thames Estuary. There the great beds of native oysters are rapidly growing smaller because of intense competition from hardier organisms like slipper limpets and barnacles, which being better adapted to the present-day environment are robbing the oysters of their food and squeezing them out of the breeding grounds.

Equally fierce competition of this kind goes on continually in the plant world where the weed stifles the wheat plant by robbing it of moisture, where the oak tree stifles the undergrowth by robbing it of light.

Between individuals of the same animal species there is often in addition a competition with particularly direct effects on evolution—the rivalry between the males at the breeding season.

In many types of herd animals the bulk of the offspring are sired by a few dominant males which fight for overlordship of the females, and so prevent the weaker specimens from passing on their undesirable genes.

In some species of birds a similar result arises from the fact that the male must be in possession of a tract of territory, which it has to defend, before it can get a female to mate with it.

The existence of the capacity in the females of some species to exert a choice at mating gives importance to certain mutations which at first sight appear to be of no significance. In a certain wild species of *Drosophila*, for example, it has been shown experimentally that the females rejected the mating advances of yellow males which had arisen by mutation whilst readily accepting the normally coloured males.

Dominating all this competitive interplay and swinging the balance of the existence struggle in unpredictable ways are the great physical forces of climatic and geological change.

Those organisms which, as a result of their genetic make-up, are best adapted to new conditions—as the mammals apparently were, at the end of the Cretaceous period for example, —survive. The misfits go to extinction.

Of course the survival of the fittest is not an infallible law. As we all know, chance is an important factor in the life of every individual. But in the main the law holds.

The general process whereby all these influences, organic and climatic, combine to weed out the weaklings and retain the best stock is called *natural selection* to distinguish it from the *artificial selection* practised by man in breeding his domestic animals.

Although the principle of automatic selection by natural influence seems obvious now no one had stated it clearly until 1859 when Charles Darwin put it forward in the form of a carefully reasoned argument.

What led Darwin to put the theory of natural selection forward?

He based his argument on two main observations:

(1) That although many organisms produce great numbers of offspring—the cod, for example, lays millions of eggs, whilst the tobacco plant produces thousands of seeds—the populations of each species remain more or less the same.

(2) That although the individuals of any given species conform to a basic pattern they are never exactly alike.

Observations of the fantastically high mortality rates in nature led Darwin to the concept of an unceasing struggle for existence. This coupled with the second observation led to the principle of natural selection. For, Darwin argued, since the individuals of a species are observably different they must differ in their fitness to cope with life in their normal environment. Therefore, as a result of the struggle for existence there will be an automatic survival of the fittest.

All this seems little more than common sense now but that is true of most leaps in human thought once they have become generally accepted. When Darwin first put forward his views in print he was met with ridicule and abuse.

There were certainly points in which Darwin was mistaken, and critics have persistently played them up in the illogical belief that by disproving some of his supporting arguments they would automatically discredit the entire evolutionary concept.

The best-known and most vulnerable of these weaknesses concerns the question of how the giraffe came to have such a long neck.

Darwin argued that since giraffes feed chiefly on the leaves of trees, those with the longest necks would be the most certain to survive during times of great dearth, for they would be able to reach food denied to shorter specimens. Each dearth, therefore, would tend to weed out any short-necked individuals and leave only those with long necks to breed. This process, repeated over thousands of years, Darwin believed, would account for the excessive length of neck shown by modern giraffes.

At first sight the theory seems reasonable. Tallness in giraffes is presumably an inherited feature, and the individuals selected for survival by the dearths would owe their exceptional height to the possession of special genes. They would, therefore, tend to pass on their tallness to following generations, in which more mutations towards still longer necks would occur, eventually to be selected in their turn by another dearth.

On closer study, however, three serious objections to this argument emerge:

(1) During dearths severe and frequent enough for natural selection to operate through leaf-shortage the wastage of young giraffes would be so great as to threaten the species with extinction.

(2) Under such extreme conditions of drought the grass-eating antelopes and zebras of Africa would have also been so short of food that it is difficult to see why they too did not develop the leaf-eating habit and consequently the excessively long neck.

(3) Bull giraffes tend to be several inches taller than the cows so that during each dearth males would be naturally selected at the expense of the females—another factor likely to lead to rapid extinction.

There is no getting round these objections. In the writer's view they definitely show that Darwin was wrong in the way he applied his concept of natural selection to this particular case. But equally definitely they do *not*—as some people have suggested—disprove the concept itself.

As the writer has recently pointed out there is an alternative way of explaining the evolution of the giraffe's neck by natural selection, which is free from these criticisms:

The most extraordinary anatomical feature of the giraffe is not the length of its neck but the length of its forelegs. (You can prove this for yourself in any natural history museum which has a giraffe skeleton.)

This extreme length of leg gives the animal a phenomenal stride so that in spite of a rather slow galloping rhythm it can move at speeds up to 32 m.p.h.

The giraffe is actively preyed upon by lions and leopards.

So it is reasonable to explain the exceptional length of its forelegs in the same way as we explain the long legs of the zebra—i.e. they are the end result of a relentless run-or-be-killed struggle in which the fastest individuals—in this case the giraffes with the longest legs—are selected for survival.

Now like other cud-chewing animals the giraffe requires a plentiful supply of water. The development of an increasing shoulder height would therefore necessitate the development of a means of getting the head down to water level.

Horses and antelopes solved this problem by the simultaneous development of a proportionately long neck. The writer contends that the giraffe solved it in the same way.

That the neck has elongated to a degree only just sufficient to keep pace with the increasing length of the legs is suggested by the fact that the giraffe has to splay its forelimbs awkwardly to drink.

In this light, natural selection would seem to have operated continually in favour of increasing length of neck instead of intermittently during discontinuous periods of drought as necessitated by Darwin's theory.

It is further contended that the leaf-eating habit of the giraffe is a concomitant of the development of the long neck and not the cause of it. It would seem reasonable to suppose that the ancestors of the giraffe were grass-eaters and that with the lengthening of the neck a new source of food became available resulting in a change of feeding habit. This contention is supported by the fact that giraffes eat grass if leaves are not available and thrive on hay in zoological gardens.

It may be argued that the giraffe's closest living relative, the okapi, is a leaf-eater although its neck is no longer than that of a horse. The okapi, however, lives in dense forests where it has no option but to eat leaves.

Is the principle of the survival of the fittest supported by any experimental evidence?

There are many experiments and precise observations which support it.

One interesting series tested the survival value of camouflage. For seven weeks 288 specimens of a certain kind of fish were kept in a black tank and as a consequence became very dark in colour. The same number of fish kept in a white tank for seven weeks became pale grey. All the fish were then put together in a grey tank and when they were thoroughly mixed up tame penguins were allowed to capture and eat them. Of 270 fish eaten 61 per cent were dark in colour and 39 per cent were grey. In similar trials in which the birds were allowed to capture the mixed fish in a black tank 73 per cent of the fish eaten were grey.

The difference in colour between these fishes was not the result of mutation, being, in fact, purely an environmental effect, but nevertheless the experiment shows that colour can greatly influence fitness to survive and, as we have seen, colour is a feature particularly prone to mutation.

Other experiments which clearly show the survival value of a protective colour have been carried out with aquatic insects. Water-boatmen beetles, some normally coloured, others painted bright red were put into a tank containing voracious dragon-fly larvæ. Far more of the conspicuous red beetles than the naturally camouflaged individuals were captured and eaten.

Direct evidence of the survival value of colour *mutation* has been provided by observation on certain moths.

In many animal species individuals occasionally arise which, as a result of a mutation in a colour gene, are darker than the average. Black sheep are the best known examples of these so-called *melanic* forms.

As a rule a melanic form is at a disadvantage in nature, for its dark shape makes it conspicuous to its enemies. This fact is well shown by certain British moths: the melanic forms which they frequently produce by mutation, although dominant, are usually quickly wiped out in the open countryside because they are so much more conspicuous to birds and other creatures preying on them. But it so happens that in the industrial towns these moths have a considerable camouflage advantage over their normal brethren for their blackness matches the soot deposit on the trees and buildings. And it is a fact that in industrial areas melanic forms of several moth species—the peppered moth, grey dagger and mottled beauty, for example—have increased considerably during the last century, completely ousting the normal forms in some areas.

(The mutation which causes the melanism also appears to confer increased hardiness, and this no doubt has played some part in establishing the mutated forms.)

These observations on moths do more than illustrate the principle of natural selection. They also show that a mutation which has been a disadvantage when it has happened in the past can become a definite asset as a result of a change in the environment. We have seen definite evidence of this in the way originally harmful mutations—hornlessness, for instance—have become advantageous as a result of domestication.

Further evidence is provided by the results of field experiments with *Drosophila* fruit flies. Equal numbers of normal flies and of a wingless variety which had arisen by mutation were released on a sea-shore. Counts taken later showed that the wingless forms had established themselves in the new environment more successfully than the normal flies. Apparently too many of the winged flies were blown out to sea by the wind.

The sea-shore is not a normal habitat for fruit flies, but these experiments show that if *Drosophilas* were ever driven to colonise it a mutation which could, on the face of things, be hardly more disadvantageous would in fact be a great asset.

The fact that a given mutation tends to recur time and time again is a decided advantage to the species, for the day may come when it will be useful. No doubt this applies to many mutations which when they first arise are neither harmful nor advantageous. Since such neutral characters would not be rapidly weeded out by natural selection the genes responsible for them might persist until such a time when, as a result of environmental changes, they became useful.

This argument no doubt also applies to those recombinations of genes which are brought about by crossing-over and other chromosomal changes. A reshuffling of the genes which proves to be of no immediate advantage may turn out to be useful later on.

The changes which brought about warm-bloodedness in the prototype mammals probably had such a delayed action. In the warm climate of the dinosaur ages blood at a constant temperature was of little advantage but became overridingly important when the climate grew colder.

A good example of a character change brought about by the action of natural selection in a changing environment has been provided by a study of a colony of crabs.

A breakwater was built in the bay where the crabs lived and this caused an increased amount of silt to be deposited on the sea-bottom. It seems that those crabs with wide shells fared badly under the new circumstances because silt accumulated in their gill chambers and interfered with breathing. At any rate during the five years following the installation of the breakwater the average shell-width of the crabs living there became increasingly smaller due, it is believed, to the elimination of those individuals carrying genes which produced wide shells.

Is it generally believed then that evolution is a haphazard affair proceeding by the action of natural selection on mutations and other accidental gene changes?

Yes. All organisms tend to undergo mutations and other changes of the gene complex from time to time and a small proportion of such changes are likely to prove advantageous in the struggle for existence. The agents of natural selection usually favour these improved individuals in competition with the original types which are thereby gradually supplanted. In this way organisms on the whole become increasingly better adapted to their outside environment. This process of adaptation usually involves specialisation of bodily form and function so that organisms gradually increase in complexity or, as we say, evolve.

An organism's chance of survival does not always depend upon visible characters. Thus two strains of the same species of insect may look identical yet, as a result of some mutation which has conferred a physiological advantage, one may be much better fitted to survive in a particular environment than the other.

This fact was well shown by rather ingenious experiments involving two seemingly identical strains of a particular species of fruit fly. One of the strains came from Tomsk in Siberia, the other from Tripoli in North Africa.

The species of fruit fly in question is quite different from the *Drosophila* fruit fly generally used in experiments and in a mixed population the two species can easily be distinguished.

A scientist therefore arranged an experiment in which 150 eggs of the Tripoli strain were placed together with 150 eggs of the ordinary fruit fly in a small bottle containing insufficient food for the full development of the 300 larvæ hatching from the eggs. Naturally there was great competition for the restricted food supply and some of the larvæ died in the struggle. When the survivors were counted the scientists found that considerably more of the ordinary fruit flies had survived, the proportion being less than two Tripoli flies to three ordinary. This proportion held fairly uniformly when the experiment was repeated.

The scientist then carried out all the experiments again using 150 flies of the Tomsk strain instead of Tripoli flies. The results were quite different, the proportion of survivors being roughly fifty-fifty.

This proved that although the Tripoli and Tomsk strains of fly look alike, the flies from Russia are much better fitted to survive the adverse conditions of the experiment than are the North Africa flies.

There must, of course, be some inherited internal difference between the two strains affecting physiology to account for such different survival rates.

It is understandable that many people reject the suggestion that an organism as complicated as man could ever have arisen by such a haphazard process and prefer instead a belief that evolution has proceeded in accordance with an ordered plan. But a closer study of the development of man and animals in general invalidates this criticism and denies the existence of such *programme evolution.*

Incomplete as the fossil record is it shows quite definitely that organisms have not as a rule progressed *steadily* towards increased efficiency and adaptability to circumstances as one would expect if evolution were ordered. Frequently, in fact, an evolutionary step has had quite the reverse effect. For all that natural selection ensures is the survival of those individuals which are fitted to survive at the particular moment. Usually this does result in progress for the species as a whole, but sometimes it spells disaster.

The development of horns in the Irish Deer (often wrongly called an elk) which lived in Pleistocene (No. 16) times is a good example of an unfortunate evolutionary step. The males ended up with massive antlers sometimes nine feet across.

Apparently this was the result of the fact that the males with the biggest antlers usually won the rutting season fights for supremacy over the females. Such *sexual selection* would ensure the perpetuation of any mutations towards the development of bigger antlers—a trend which, when it reached its eventual absurd proportions, must have hastened the extinction of the species, for deer with such heavy horns must have found it difficult to escape from carnivores and from men.

It is easy to think of other cases where similar sexual selection could have serious consequences for the species. Certain cock birds which carry out a courtship display in front of the females are heavily feathered. If the females preferred as mates those individuals with, say, the longest tails, males would tend to arise with tails so long that they might find it increasingly difficult to escape attack. Such a tendency could lead to the rapid extinction of a species.

We have seen a case where female flies preferred to mate with dark-coloured males rather than yellow ones. If a reverse preference were to arise as a result of some gene-change it could lead to rapid extinction, for yellow flies might be much more conspicuous to their enemies.

Exaggerated development of general size seems to have become a factor in the extinction of whole groups of animals, in particular the great reptiles and some of the early mammals like *Diprotodon*—a marsupial relative of the kangaroo almost as big as an elephant.

It must surely be admitted too that the tremendous wastage, which, as the fossils show, has characterised evolution throughout time, is more consistent with trial and error experiment than with ordered planning.

The fossil remains of more than 300 extinct species of elephants provide a particularly striking testimony that the trial and error principle has dominated the origin of species.

A million years ago elephants ranged over almost the whole of the northern hemisphere. Skulls from these and earlier times show that almost every conceivable form of tusk development was exploited. The earliest elephants had tusks in both jaws. Then came some forms which had tusks only in the lower jaw whilst others, like existing elephants, had only upper-jaw tusks. The dinotherium had tusks which curved sharply downwards : the huge tusks of the mammoth curved upwards and outwards : the mastodon had no tusks at all.

It is probably true to say that there has never been a straight line of evolutionary development. Always there seem to have been experimental branchings in many directions. Some branches were highly successful, expanding into main lines of the evolutionary tree from which further experimental types arose. Others, locally successful, remained as small but persistent twigs. The rest were quickly stunted and then extinguished in the organic struggle.

This irrepressible experimentation shows up sharply within a single sub-order like the elephants, but to see its full expression broad examination of one of the great natural classes—the reptiles for instance—is required.

We have seen how from a small localised amphibian stock there streamed a multitude of fantastic creatures. There were big reptiles marvellously adapted to life in the open sea. There were small reptiles beautifully adapted for flight. There were reptiles of every conceivable size and type adapted for different kinds of life on land—in the swamps, the forests and the deserts. Some were herbivorous : some carnivorous. Some were successful : others failed.

Scientists have given a name to a great evolutionary outsurging of this kind resulting in the population of almost every environmental niche. They call the process *adaptive radiation*, and it appears to be entirely due to the action of natural selection on innumerable small changes in the gene complexes of the organisms involved.

Adaptive radiation is the method by which man has descended. From an original ape-like stock there radiated successive streams of experimental hominoids ending in scores of races each adapted to life in special environments ranging from Arctic wastes to tropical forests. Such forms as Piltdown and Neanderthal man are representatives of the many experiments which ultimately failed, and were eliminated by natural selection as ruthlessly as were the diplodocus and the pterodactyl.

In addition to all this there is the experimental evidence observed in both animals and plants that mutations occur entirely at random. If we divide a population of *Drosophila* flies into two parts and keep them in quite different environments the same mutations will occur with equal frequency over a long period in both. Those mutations which are advantageous in one of the environments will be just as likely to occur in the other where they may be useless or even deleterious. And this goes for all other organisms which have been continually tested in this way. There is no evidence whatsoever that mutations occur in such a way that organisms evolve in particular directions, as we should expect if the whole process were ordered on programme lines. Indeed, as we have seen, most mutations are decidedly disadvantageous.

Would it be correct to say then that apart from its action through natural selection the environment has no moulding influence on the evolution of species?

It is reasonably well established that small mutations and gene recombinations can account for all the character changes which organisms have ever undergone. It is also well established that they occur just as frequently whether the environment is harsh or benevolent, changing or relatively constant.

To summarise it would be fair to say that this modern viewpoint on evolution harmonises to a large degree the conflicting theories of the past. There is no longer any question of whether heredity or environment controls the process. The fact is that both are equally important, evolution being the result of constant interplay between the two.

We still have a great deal to learn about this interplay in the production of new species. We understand very little about the sudden forward leaps which have characterised the evolution of animals, for instance. The fossil record shows they are relatively rare—thus there have been only six during the whole 500 million years of vertebrate development—the emerging of the first fishes, the first amphibia, first reptiles, first mammals, first birds and the first men.

If there is no programme in evolution why doesn't it go backwards towards simplicity as well as forwards towards complexity?

It sometimes does go into reverse. If an organism finds itself in circumstances where there is little competition and where it is sheltered from the usual harsh pruning effects of environment it may undergo *degeneration* which, from the structural point of view, is the reverse of evolution—a change from complexity towards simplicity.

Many parasites have undergone such degeneration. Of these a creature called *Sacculina* which parasitises crabs is a good example.

The larval stages of *Sacculina* are free-swimming organisms very similar to those of the crustaceans called barnacles. The adult stage, however, which lives in a crab has no resemblance to any crustacean, lacking eyes, limbs, mouth and food canal and having only a feebly developed nervous system. Its whole body, in fact, is little more than a bag sending out fine absorptive tentacles into the crab's tissues.

There seems to be little doubt that *Sacculina* represents a type of barnacle which, instead of just using crabs as somewhere to anchor, has actively parasitised them and in the course of time has undergone structural degeneration as a consequence.

Degeneration is always to be expected under such circumstances because the natural selective agents which would suppress disadvantageous mutations do not operate. And in many parasites—tapeworms for instance—the rate at which such mutations establish their influence is greatly accelerated by the fact that they are hermaphrodite and fertilise their own eggs with their own sperms. (Remember that inbreeding greatly speeds up the rate at which recessive mutations show themselves.)

It seems general in fact that characters which, as a result of a change in environment, cease to be useful are gradually lost.

Doubtlessly there are occasions when reverse mutations which would be advantageous to a species are obliterated by natural selection. Thus a series of mutations reducing antler size in the Irish deer might have saved that species from extinction but it seems that sexual selection would have prevented any such trend.

Does this explanation apply equally well to the degeneration of organs like the appendix in our own bodies?

Yes. It seems that not only is natural selection the means whereby an organ reaches a peak of development: it is also the means whereby the organ remains in that condition. In other words for an organ to persist in a highly developed state the agents of natural selection must act continually in its favour. If their vigilance is relaxed adverse gene changes—mutations and recombinations—pile up and bring about degeneration.

The human eye is a good example of an organ which is kept at the peak of efficiency by the continual action of natural selection.

Because eye efficiency is a critical factor in the daily life and death struggle of most wild animals it is extremely susceptible to the influence of selective forces. Mutations giving any worthwhile degree of advantage are likely to be selected: adverse mutations are certain to be rapidly extinguished. We can be quite sure from this and other evidence that the eye reached its present degree of efficiency very early in man's evolution. It seems that as a result of mechanical and other limitations the human eye cannot be further improved. But there are several eye defects clearly due to gene mutations which show that without the beneficent influence of natural selection the eye could quickly degenerate. (It is true that by his humanitarian laws man tries to take some of the sting out of natural selection in so far as it applies to his own species, but it nevertheless holds that people with serious inherited eye defects are less likely to propagate themselves than are normal folk.)

This important contention—that without the positive influence of natural selection an organ cannot remain in a well-developed condition, much less advance further—is supported by the eye-degeneration shown by fishes and other creatures living in caves. Eyes are no advantage in total darkness and with no selection " pressure " to keep them up to the mark they degenerate to mere vestiges.

The argument seems equally applicable to the human appendix which was probably bigger and may have had a definite function in the distant days when man's diet was entirely vegetable. It also fits such cases as the wing degeneration shown by the ostrich, cassowary and emu.

This explanation of degeneration following disuse must not be taken as supporting the inheritance-of-acquired-characters theory. According to that theory if throughout my early life I weakened my eyes by continually living in a dark cave I would automatically pass on some element of that weakness to my children who would consequently tend to have weak eyes at birth. If they decided to live in darkness their eyes would acquire an additional weakness during their life and according to the theory their offspring would have still weaker eyes at birth, and so on until after many generations of cave-dwelling my descendants would be born blind.

Now there is no worthwile evidence to support such a contention. It is pretty certain that blindness from eye-degeneration would be a consequence of a long-sustained troglodyte existence, but it would be the result of chance mutation flourishing in the absence of natural selection.

How long on the average does it take a favourable mutation to supplant the normal form?

It depends on what degree of advantage the mutation confers and on two other factors:

(1) Whether the mutated gene is dominant or recessive.
(2) The size and breeding habits of the population in which it occurs.

We have seen in the case of the melanic moths that a dominant mutation conferring an immediate clear-cut advantage can establish itself within a century. But we must face up to the fact that in the wild state most mutations likely to prove advantageous are recessive.

As already stated recent research has shown that a recessive gene may exert some effect on an individual when present in the single dose and when its full action is suppressed by the corresponding dominant gene. Though such an effect may be too slight to be easily observable it may be sensitive to the action of natural selection and so influence the individual's chance of survival, usually lowering it—for most mutations are disadvantageous—but slightly raising it on occasions. In this light then a recessive gene need not have to wait until it chances to meet up with another gene like itself before it can exert some influence on the evolution of the species.

In the case of recessive mutations such as these the bigger the populations in which they arise the sooner will their influence be established. The reason for this is that in big populations mating is more likely to be random and more animals will consequently inherit the changed gene than if mating were restricted within a small group. And the greater the number of animals on which the mutation can exert an influence the quicker will natural selection be able to work effectively.

It is unlikely, however, that the action of recessive mutations in the single dose has been generally sufficient to account for more than a small proportion of the evolutionary process. And in any case there can be little doubt that anything which increases the chances for advantageous recessive mutations to combine in the double dose and so exert their full effect will speed up the rate of evolution. This is where the breeding habits of the population prove so important.

The influence of a recessive gene which must be present in the double dose to produce a significant effect will spread much more rapidly in a population which practises a considerable degree of inbreeding for, as we have seen, inbreeding greatly increases the chances for recessive genes to combine.

In very small populations a considerable degree of inbreeding is inevitable, but this will not normally result in rapid evolution for the smaller the population the smaller the number of mutations which will occur in a given time. This point has been proved in experiments with fowls. With flocks of less than fifty fowls it has not been possible to raise egg production after eight generations of careful selection but a marked improvement can be obtained with much bigger flocks. (It must constantly be borne in mind that inbreeding does not increase the rate at which mutations occur but simply improves the chances for recessive mutations, which would otherwise lie dormant, to express themselves.)

Now there are some animals which exist in populations big enough to yield a fair supply of mutations and which practise a considerable degree of inbreeding. Elephants and deer are good examples. Wild elephant herds are served by a few dominant bulls which appear to mate regularly with their own daughters and are often succeeded by their sons. At the same time there is some degree of cross-breeding between different herds because young bulls occasionally stray from one group to another. Stags practise a similar form of polygamy and inbreeding.

It is not surprising therefore to find that elephants and deer are among the animals which have had the most rapid rate of evolution in spite of the fact that they breed slowly. Thus the fossil record shows that since Cretaceous (No. 11) times there have been more than 300 species of elephants only two of which are still alive.

It seems likely that in most herd animals the rate at which advantageous mutations are established is speeded up by some degree of inbreeding. For instance the great herds of cattle living a semi-wild life on South American ranches are really composed of more or less self-contained groups of forty to a hundred beasts which recognise one another and cling together.

We must now consider the case of a population which has once been numerous but becomes reduced relatively suddenly by disease, cold or some other environmental factor.

We have seen that in a big population in which the animals mate at random a recessive mutation occurring in one individual is much more likely to be inherited by individuals of later generations in the single than in the double dose. So during the time that a random breeding species is numerous recessive mutations should tend to collect within the widespread population without showing up. If such a population undergoes a drastic reduction in numbers as a result of some environmental factor acting over a wide area the survivors might be left in small isolated groups and so be forced to practise some degree of inbreeding. This should provide the opportunity for long-hidden recessive genes to combine in the double dose and so make their appearance as changed characters.

Following a catastrophic population drop then, we should expect a long-established species to give rise to individuals showing new character combinations.

How these changes would affect the further evolution of a species would depend on whether it happened to be already specialised or whether it still had " plasticity ".

What is meant by " plasticity "?

Plasticity means the possession of genes capable of giving rise to a series of mutations and recombinations a relatively high proportion of which can ultimately be turned to evolutionary advantage. The species which gave rise to great new groups—the prototype reptiles and mammals, for example—must have had an exceptionally high degree of plasticity.

In contrast to plasticity is " specialisation ". The genes of a specialised organism—one nicely adapted to a particular environment—must have already undergone a long series of mutations and recombinations certain of which have been naturally selected. Any further change in the gene-complex of a specialised animal is obviously especially likely to be deleterious, for the more intricately organised the complex has become the greater is the likelihood that a chance disturbance will throw it off balance.

These differences between plasticity and specialisation were highlighted by the separate fates which overtook the early mammals and the contemporary dinosaurs at the close of the Cretaceous (No. 11) period.

The geological record tells us quite clearly that towards the end of Cretaceous times some factor brought about a great reduction in the numbers of every species of dinosaur. What this factor was is uncertain but we know that it could not have been active competition from the mammals which were then much too small and defenceless. (The ingenious suggestion that small mammals brought about the extinction of the dinosaurs by sucking their eggs does not account for the fact that the viviparous dinosaurs were also extinguished at the same time.)

It has usually been assumed that the change which brought disaster to the dinosaurs did not affect the existing mammals adversely but instead provided conditions which enabled them to multiply both in numbers and species.

The writer thinks that it is more reasonable to suppose that any change—and it was a world-wide change—which so drastically reduced the great reptilian population would be more likely to have had a similar effect on the existing mammals than to have left them untouched numerically. And if we do suppose that the mammals also suffered a great reduction in numbers at the end of the Cretaceous period it seems to be easy to account for their subsequently rapid evolution simply by applying our previous arguments about inbreeding.

During the 60,000,000 years or so between the Triassic (No. 9) and the middle Cretaceous periods when the unspecialised mammals were apparently numerous, there would probably be a tendency for recessive mutations to collect within the various species. For it is unlikely that these early forms had the group-breeding instinct highly developed and with big populations the chances of inbreeding would be low.

A relatively sudden reduction in numbers would, however, force the remnant populations isolated in small groups into a considerable degree of inbreeding. So following a major climatic change or similar disaster we might expect the relatively sudden appearance of a large number of new and divergent characters due to the combination of recessive genes. In such plastic prototypes a comparatively high proportion of these mutations might be changed to evolutionary advantage.

The better adapted individuals would be naturally selected and as the populations began to increase their influence would be rapidly established.

Different character combinations might be selected within the different groups and by the time the separate populations grew big enough to overlap in range some of them might be sufficiently different to be intersterile. In this way there might be a relatively sudden origin of many new species.

It is, of course, an established fact that immediately following the Cretaceous the number of mammal species increased very rapidly. All the main groups of mammals existed in Eocene (No. 12) times.

In the light of these ideas what would we expect to have happened to the dinosaurs as a group following the great reduction of their numbers in Cretaceous times ? During the many millions of years when they were numerous they too should have accumulated large numbers of recessive mutations which might be brought to light by the increased degree of inbreeding forced upon them after their numerical decline and probable isolation into small groups. But because of their specialisation most of these mutations would be likely to prove disadvantageous and we might therefore expect the relatively sudden origin of bizarre new species which would hasten the final extinction of the group.

We have seen that this is just what happened. Among the last of the dinosaurs were species with absurdly large and sculptured skulls often carrying useless spines.

Does this theory that comparatively sudden reductions in populations have speeded the development of new groups as well as the extinction of old ones apply to other cases apart from the reptiles and mammals?

It seems to apply to most cases for which the fossil evidence is good enough to provide sound guidance. For example, it would explain why the rapid decline of the trilobites in Devonian (No. 6) times was accompanied by the equally rapid rise of the fishes which had been in existence for some millions of years. It would also explain why the final crop of trilobite species was characterised by an absurd degree of spininess.

A fantastic number of fish species suddenly came into existence in early Devonian times. May this not have been because the populations of the unspecialised Silurian fishes were also drastically cut by the unknown marine change which brought extinction to the trilobites and so were forced to practice a higher degree of inbreeding? It seems to be more than a coincidence too that the bony fishes which apparently arose in late Triassic (No. 9) times had to wait 50 million years until the Cretaceous period—the time of the change which killed off the marine reptiles—before they could expand, when they started budding off new species with exceptional rapidity.

Unfortunately we know too little about the development of the amphibians from the fishes and of the reptiles from the amphibians to speculate about the evolutionary mechanisms involved there.

Is there any evidence from existing species that reductions in established populations can speed up the appearance of new characters?

British biologists have reported on an isolated colony of fritillary butterflies which underwent considerable fluctuations in numbers over a period of years. Between 1881 and 1897 the species was very numerous, occurring in great clouds during the few weeks of the year when the insects were on the wing. The population then began to decline and by 1920 the butterfly was extremely rare. Soon after this, however, it underwent a rapid increase and became very abundant again.

During the first period when the butterfly was abundant the amount of variation between different individuals was very small. But when the numbers were rapidly increasing following the great reduction an extraordinary outburst of variation occurred. The character differences affected size, shape and colour, many of the individual butterflies being deformed. It is especially interesting that when these deformities had been weeded out by natural selection and the species settled down to a constant form again it was a form quite different from the original one.

It might reasonably be asked why the American bison did not throw off new species when it was forced to undergo inbreeding as a result of the reduction of the total population from millions to just over a thousand late in the last century. The answer would be that the bison is one of those animals which though moving in great herds really lives within small cohesive groups which practise a considerable degree of inbreeding. Recessive genes are, therefore, not so likely to collect in such a species for they will show up soon after they arise and quickly be encouraged or weeded out by natural selection. A species with the breeding habits of the bison would, therefore, be expected to evolve rapidly like the elephants, giving rise in the course of its journey towards specialisation to many offshoots but being relatively unaffected by population fluctuations.

How many mutations are needed to change one species into another?

It is impossible to answer this question satisfactorily for at least three reasons:

(1) Too little experimental evidence is available of attempts to change one species into another by X-rays and other artificial means.

(2) The number of mutations required will obviously vary with the extent of the change brought about by each one.

(3) There is no clear-cut definition of the word " species ", so the opinions of different authorities would vary as to the precise point at which sufficient change had been undergone to warrant reclassification of an organism as a new species. We have already seen an example of this confusion in the case of the hooded and carrion crows.

It is possible, however, from the fossil record to give a fair idea of the average time taken by some animal groups to undergo a series of character changes sufficiently distinct to be generally accepted as constituting a species change.

Scientists have calculated that in the case of the fossil horses which evolved relatively rapidly it took about 100,000 generations—say 500,000 years—for a new species to evolve, whilst about 1,000,000 generations covering about 5,000,000 years were needed to bring about changes so great that the new types have to be classed as belonging to a different genus.

Other animals, especially invertebrates, seem to have evolved much more slowly. For ammonites—a group of fossil molluscs which have been widely studied—it has been calculated that about 20 million years were needed for one genus to change into another.

These are, of course, merely rough average figures. As we have seen the rate of evolution varies greatly being, apparently, exceptionally rapid in some groups after a reduction in population.

This relatively sudden origin of many new species has been called *explosive evolution* and it shows up just as sharply in a fine-focus study of a single genus as in a wide survey of a major group.

For example, the fossil record shows that the genus of sea urchins called *Salenia* underwent a phase of explosive evolution in the Cretaceous period (No. 11) but since then has hardly evolved at all.

In attempting to explain this phenomenon by the same principles we used to account for the rapid rise of the mammals it is interesting to note that a period of explosive evolution is nearly always preceded by a lag-phase of a few tens of millions of years and often—in the case of *Salenia* for instance—is quickly followed by a catastrophic drop in the number of species. The writer has suggested that the lag-phase represents the time during which the original species is numerous and building up a collection of recessive genes whilst the explosive period follows a drastic reduction in the population leading to the isolation of small groups and consequent inbreeding. A catastrophic drop in the number of species following a burst of explosive evolution is often to be expected, for the bulk of the species split off in this way from an already specialised form will most likely prove to be evolutionary failures and quickly become extinct.

Are there any species which seem to be going towards extinction now?

This is another question which cannot be answered satisfactorily because the evolutionary fate of many animals, especially the larger species, will depend so much on the measure of man's interference. Thus whilst man has been directly responsible for the elimination of forms like the American passenger pigeon, which would normally have remained numerous, he may by enlightened conservation save species which would naturally become extinct.

It would seem, however, from the past evidence that those creatures like whales and elephants which have reached a very great size must eventually become extinct.

The unwieldiness which usually accompanies excessive size seems to have been a major factor in the elimination of many species of fishes, reptiles, birds and mammals.

The reason for the trend towards increasing size in the evolution of each group is not clear except possibly in the case of the mammals. It has been shown that in those mammals which give birth to several young at a time there is active competition between the embryos for the available food supply inside the womb. In the pig, for example, up to 20 per cent of the embryos originally conceived die at an early stage of their development and are absorbed. In wild rabbits the proportion of embryos eliminated in this way is probably between 30 and 40 per cent. It seems to be the biggest embryos which survive, so this competition may continually select any mutations towards increased size and in the course of time raise the average size of the adults.

In addition to making the species more unwieldy increasing size brings a further disadvantage. The bigger the embryos the longer is the period of gestation required to produce them and this, of course, cuts down the breeding rate.

At first sight this ingenious theory would not appear to account for the great size of the whales and elephants, for these animals produce only one offspring at a time. It may be, however, that several embryos are conceived in each case and that owing to intense competition only one survives. Too little is known about the reproduction of whales and elephants to decide this issue.

Another point which helps to explain the evolutionary disadvantage resulting from excessive size is the fact that the glands which control growth also affect fertility.

Chief among these glands is the pituitary—a small knob of tissue attached to the underside of the brain and discharging its juices into the bloodstream. Over-secretion of the pituitary gland produces excessive growth : it also reduces fertility.

In the light of these remarks it is especially interesting to note that in both body size and weight man is increasing rapidly. You can prove this for yourself by visiting any museum where suits of armour are on show—the Tower of London, for instance. Most medieval armours would not fit the average 16-year-old boy of today. Comparison of Egyptian mummies with modern Egyptians gives further proof of man's rapid growth during the last few thousand years.

The significance of this increase is uncertain. A large proportion of it is an environmental effect due to better feeding and housing and operating separately on each generation without hereditary effect. Thus within a single generation the Japanese living in America have increased their average height by two to three inches. But the long-term trend is probably the result of inheritable changes in the human gene complex.

If it continues without appropriate changes in body structure it might be disastrous, for in its present conformation the human frame is not far from the size limits set by engineering considerations. Legs of conventional shape would not support very much bigger bodies. The proportionate sizes of the internal organs would have to be quite different and so on.

Is it possible to predict the general course of evolution in the future?

No. Man has become so completely dominant on the earth that he will control the future course of evolution to an extent which makes it impossible to draw useful comparison with the past. To predict the course he will follow is to predict history.

Astronomical evidence suggests that the world is destined to undergo climatic changes as severe as those of the past. It seems for instance that A.D. 21,000 may see the start of an Ice Age which will affect most of Northern Europe as seriously as did the last southward advance of the polar ice.

These will be testing times for existing species and opportunities for new ones. No doubt in a few more million years dominant plant and animal species will have become visibly different from their present-day representatives. But there is good reason to believe that no existing animal group is likely to branch out into important new lines. The amphibia and the reptiles have had their day. The mammals, birds and fishes seem to have exploited every field open to them. Every group seems to be too specialised for further advance. Nothing can be expected from the backboneless animals: the dominant invertebrates—the insects—were already more or less at an evolutionary full stop 30 million years ago.

As for plants it is significant that no important advances have been made since Cretaceous (No. 11) times.

It would seem then that any important evolutionary progress that occurs will be made by man himself. Specialised as *Homo sapiens* there is no reason to suppose that the species has reached the limit of its mental development. It is true that there has been no observable trend of mental progress since the days of the ancient Greeks, but 2,300 years is an insignificant period by evolutionary standards.

We must remember too that man is the first species theoretically capable of controlling its own evolutionary destiny by recognising adverse trends and deliberately stemming them. Whether in fact he will ever be able to organise an effective measure of genetic self-control is uncertain. The record of man's past and present political behaviour provides little real evidence for optimism.

Perhaps future students of evolution will decide that "*sapiens*" was a misnomer for our species.

APPENDIX

HOW THE PAST HAS BEEN DATED

Earlier in this book it has been stated that it is about 3,000 million years since the earth cooled sufficiently to form a solid crust. To understand how such a figure has been arrived at it is necessary to understand a little about the structure of atoms and their energy.

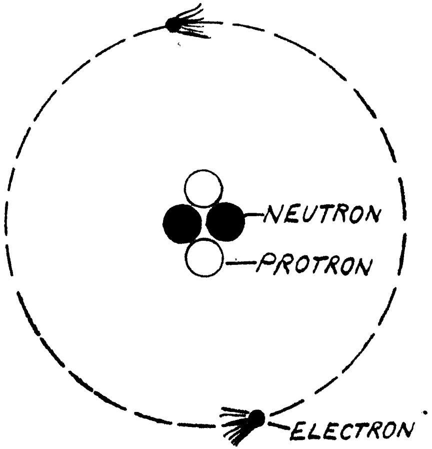


FIG. 70.—An atom of helium.

Everything in the world—the rocks, the water, the air, the plants and the animals—is made up of extremely small particles called atoms. To give some idea of the size of an atom there are about 2,500,000,000,000,000,000 atoms in a speck of matter the size of a dot over an "i".

Fig. 70 shows the structure of a typical atom—that of the airship gas helium. Two minute particles called *electrons* move like moons round a central *nucleus* itself composed of different particles called *protons* and *neutrons*.

There are 95 other kinds of atoms which all have a similar basic structure to the helium atom but each contains different numbers of electrons, protons and neutrons. Thus an iron atom has 26 electrons, 26 protons and 30 neutrons: a lead atom has 82 electrons, 82 protons and 125 neutrons: an atom of the metal uranium has 92 electrons, 92 protons and 146 neutrons.

Because of this common basic structure it should be possible for one atom to change into another by the loss or gain of constituent particles. For example, if a uranium atom could somehow get rid of 10 electrons, 10 protons and 21 neutrons it should become identical with an atom of lead. Such changes do not happen easily, of course. If they did no material would remain the same for very long. But the possibility of such *transmutations* should be grasped, for they can occur in special circumstances and form the basis of the most reliable method of dating the past.

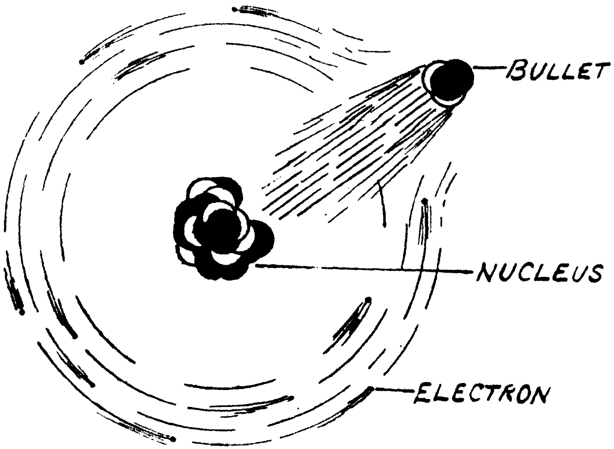


FIG. 71.—An atom of uranium exploding by throwing out a "bullet" made of two protons and two neutrons.

In addition to being exceptionally heavy as compared with say an iron atom, a uranium atom has a special peculiarity. An iron atom will remain the same no matter how long it is left, but a uranium atom will not. There comes a time in the life of every uranium atom when it explodes, shooting out a " bullet " made up of two protons and two neutrons at a speed of about 12,000 miles per second (Fig. 71). The energy which propels this " bullet " comes from within the nucleus and is therefore called *nuclear energy* or, more popularly, *atomic energy*.

Some other kinds of atoms have this instability and energy. The rare metal radium is one of them and the general phenomenon whereby atoms break down spontaneously has, therefore, been called *radioactivity*.

We have seen that if an atom loses some of its constituent particles it should automatically turn into an atom of a different kind. This is precisely what happens when a uranium atom shoots out its " bullet ". Two protons and two neutrons are lost leaving a nucleus with only 90 protons and 144 neutrons. This smaller atom has none of the properties of uranium but is identical with the atoms of another metal called thorium. In other words, when a uranium atom explodes it automatically transmutes into an atom of thorium.

The atomic breakdown process does not end with this transmutation. The thorium atom itself is radioactive and there comes a time when it too explodes, shooting out a high-speed particle and changing into something else. This process continues through several more stages until a stable atom containing 82 electrons, 82 protons and 124 neutrons remains. We have seen that such an atom is identical with an atom of lead. In point of fact the radioactive breakdown of uranium always ends eventually with the production of a stable lead atom.

We have said that every radioactive atom must eventually explode and change into something containing fewer particles. The reason for this is that so much energy went into welding together the protons and neutrons which make up the nuclei of the very heavy metals like uranium, radium and thorium that it is impossible for them to hold it indefinitely. This welding process is believed to have occurred way back in the history of the universe when the matter which now makes up the earth was hot enough to be entirely gaseous but was slowly cooling.

It was inevitable from the moment the heavy metal atoms were formed that they would eventually have to rid themselves of their excess energy by radioactive breakdown. But for reasons too technical to be explained here it seems certain that this breakdown process could not begin until the minerals containing the radioactive atoms had solidified. This solidification must have occurred at the same time that the rest of the minerals which make up the earth's crust were solidifying. In other words the time at which radioactive atoms began to break down coincides with the formation of the earth's crust and so marks the beginning of the world as a solid object.

Why all the radioactive atoms did not break down as soon as they were in the solid state nobody can explain. What happened instead was that a certain small proportion of them did break down immediately and more have been breaking down at a steady rate ever since.

It is impossible to say when any particular atom of uranium will explode just as it is impossible for an insurance company to predict when any particular one of its clients will die. But in a large lump of uranium ore containing many millions of atoms it is possible to predict accurately what percentage of the atoms will break down in any particular period just as the insurance company can gauge what percentage of its clients will die in a particular month.

These predictions of the rate of breakdown of radioactive atoms are based on laboratory experiments which have been checked many times. It is well established, for example, that one million ounces of uranium will produce $\frac{1}{7600}$ of an ounce of lead in a year.

We can see now how a study of radioactive minerals assists in dating the past. A lump of rock which contained pure uranium when it first solidified must now contain a certain proportion of lead and this proportion is a direct guide to the rock's age.

What the scientist does is to analyse the proportion of uranium to lead in the rock by chemical means and apply a simple formula worked out from laboratory measurements of the rate of breakdown to determine the age.

There are, of course, many factors which complicate this method of age determination. In the first place the scientists need to be sure that all the lead they are dealing with has been formed by the breakdown of uranium. Most of the lead in the earth's crust has not arisen in this way. It was presumably formed as lead at the time when the other stable atoms arose and has remained unchanged ever since. Obviously if a sample of rock contains some of this primeval lead as well as some lead derived from the breakdown of uranium it is essential to find out what proportions there are of each. If this is not done the calculated age of the rock will be much too high.

Fortunately there are methods of distinguishing the two types of lead.

Every atom of lead contains 82 protons and 82 electrons but some lead atoms differ in the numbers of neutrons they contain. Thus some have 125 neutrons each whilst others have only 124.

Such atoms of the same element are called *isotopes.* Both have exactly the same chemical properties (since these are determined by the number and arrangement of the electrons, which are the same in both) and are quite indistinguishable except on the basis of their different weights, one having the extra weight of an additional neutron.

It so happens that the lead produced by the breakdown of uranium is always the lighter isotope with 124 neutrons and therefore can be distinguished from primeval lead which is a mixture of different isotopes.

The technical difficulties of using these methods are further increased by the fact that the lead content of many rocks has altered as a result of weathering. Nevertheless patient research has enabled scientists to arrive at what are generally accepted as reasonably accurate estimates of the ages of minerals examined.

The oldest rocks so far tested by the uranium-lead method appear to be about 1,800 million years old. But from calculations based on the proportions of lead isotopes in primeval rocks a figure of about 3,000 million years for the age of the earth has been computed.

We have said that when a uranium atom first explodes it shoots out a "bullet" made up of two protons and two neutrons. A glance at Fig. 70 will show that the nucleus of a helium atom is made up of just four such particles. The "bullets" do, in fact, each collect two stray electrons—there are always plenty of these around—and so become helium atoms.

This offers an alternative way of determining the ages of rocks, for as with the formation of lead from uranium the release of helium dates from the time the primeval rocks solidified. And the greater the proportion of helium to uranium in the rock the older it must be.

This method has been widely used as it is not complicated by the presence of primeval material as is the lead determination method. It is not so accurate, however. Helium is a gas and over long periods of time some of it must leak away from the rock in which it is formed. The age of such a rock computed by uranium-helium analysis always tends therefore to be on the low side.

Other systems used before the radioactivity method was available have also given results which were too low. Probably the best known of these is Lord Kelvin's method based on the assumption that the earth has been cooling steadily since its formation. From estimates of its original temperature and measurement of its present temperature a maximum age of 400 million years was arrived at.

This figure has since been abandoned because there is no good evidence that the earth has cooled much since life arose on it.

Another ingenious method now regarded as unreliable was based on the study of the saltiness of the seas.

There is some evidence for the view that the seas were originally composed of pure water, formed by the condensation of steam, and have since become increasingly salty by the collection of salts leached out of the earth by rivers. A calculation of the weight of salt carried annually into the sea has been made from analyses of river waters. This figure divided into the estimated weight of salt in the sea gave an answer of 90 million. More recent calculations which have taken into account complicating factors overlooked by the early investigations have given a figure of 600 million years for the earth's maximum age but this is still very low compared with the 3,000 million years computed from radioactivity analyses.

In addition to yielding evidence of the age of primeval rocks, the radioactivity method can be used to date various layers of secondary rocks laid down since the earth's crust solidified. Most of the secondary rocks which make up the greater part of the earth's surface arose from the debris formed by the slow weathering of primeval rocks or were built up, as chalk was, for instance, from the dead bodies of animals. But some of them resemble primeval rocks in that they were forged in the heat of the earth's molten interior. Such rocks are called *igneous* rocks as opposed to sedimentary rocks. Practically all the secondary rocks which happen to be radioactive are igneous. They occur sandwiched between layers of sedimentary rock having been forced in from the side or from below under great pressure, as in the case of granite, or poured over as lava when the rocks they now cover were exposed, as in the case of basalt.

Now the statement that the formation of lead and helium from uranium dates from the time of solidification of the mineral concerned is as true for secondary igneous rocks as for primeval ones. So by analysis it is possible to determine the age of a secondary, igneous uranium ore and this, by inference, dates the rock strata between which the ore lies.

In this way the pitchblende deposits in Lower Carboniferous (No. 7) rocks in Silesia date as about 270 million years old: similar deposits in Bohemia give an age of about 220 million years to Permian (No. 8) rocks and so on.

Examination of other naturally occurring isotopes is yielding further interesting information about the past. Thus by a study of the isotopes of carbon it has been possible to show that life must have existed in early Precambrian times.

The carbon which makes up a large part of all living matter contains more of a particular isotope called carbon 13 than does the carbon occurring in minerals such as limestone. Analysis has shown that the carbon deposits found in early Precambrian rocks are of this type.

New studies of oxygen isotopes are yielding valuable evidence of the temperatures which prevailed in bygone ages.

Naturally occurring oxygen consists of two isotopes called oxygen 16 and oxygen 18, the former being much the more abundant. Experiments have shown that the proportions of these two isotopes in a chemical compound containing oxygen depend on the temperature at which the compound was formed. In the chalk built up by molluscs, for example, the lower the temperature of the water in which it was laid down the smaller is the proportion of oxygen 18 in it. The relation, in fact, seems to be so clear-cut that by the determination of the proportions of the two isotopes in a fossil shell, the temperature of the sea at the time the shell was formed can be calculated. A study of the shell of fossil cuttlefish from upper Cretaceous (No. 11) rocks in England has shown, for instance, that the sea temperature prevailing at the time the rocks were formed ranged from 17° to 27° C.

Another method which has been widely used to date rocks of the last million years or so is based on astronomical evidence.

Owing to the mutual attraction of the planets the earth does not travel along the same path round the sun each year. And because it is not a perfect sphere the earth wobbles slightly as it moves along in space in addition to rotating on its axis. The differences these variations cause in the total amount of sunlight and heat reaching any portion of the earth are slight, but taken over a period separated by several thousands of years the difference is big enough to cause important changes of climate. Only small changes in temperature are needed to bring about significant effects if they are maintained over a long period.

To illustrate this point let us consider the effects of a slight increase in the inclination of the earth's axis to the plane of its orbit round the sun. The present inclination—23½ degrees—is responsible for the fact that our summers are warm and our winters cold. If the earth's axis were perpendicular to the plane of its orbit we should have no seasons but a perfectly equable climate.

It follows, then, that if the angle of inclination were reduced by several degrees our summers would tend to be cooler and our winters warmer. The long-term effects of such a change are rather surprising.

The winters in the polar regions would still be cold enough for ice and snow to form. But the summers would no longer be warm enough to melt all the additional ice laid down each winter as they are now. Most of the new ice formed each winter would go but not all. Each winter would therefore start off with a little more permanent ice than the previous one and the visible effect of this over a long period would be the gradual extension of the ice cap towards the equator.

In other words a new ice age would develop and only following an increase in the angle of the earth's inclination would the ice recede.

Now such changes in the angle of inclination are among the long-term effects produced by the wobbles just mentioned. And it is generally believed that it was in this way that past ice ages arose.

Since alterations in the earth's axis can be predicted from astronomical data it is possible not only to predict the time of future ice ages but to date those of the past. In Fig. 72 the upper graph, A, shows past and future average summer temperatures for the northern hemisphere calculated from astronomical data. The lower graph, B, shows on the same time scale the advance and recession of the ice from the north polar regions based purely on geological evidence.

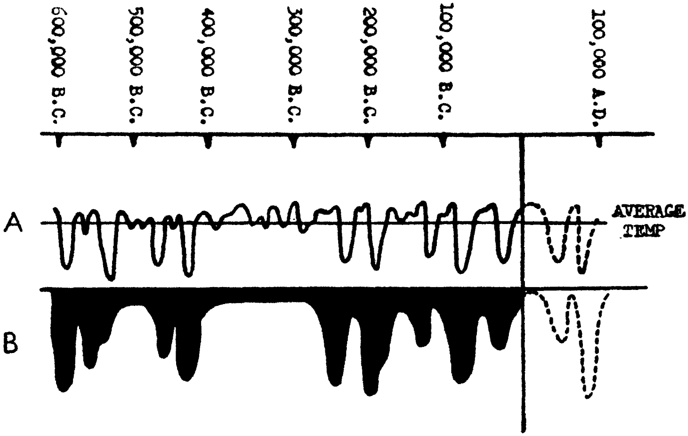


FIG. 72.—The rhythm of the Ice Ages.

The degree of similarity between the two graphs is striking evidence for the accuracy of the astronomical estimates. It clinches the belief that in Pleistocene (No. 16) times there were four major ice ages. The first began about 600,000 B.C.; the second in about 480,000 B.C., the third around 280,000 B.C., and the last, which reached a peak about 25,000 years ago, has not yet finished receding.

It will be noticed that Fig. 72 also shows future temperatures and glaciations. It suggests that the earth's climate is gradually getting warmer—a contention supported by meteorological evidence—and that the ice is on the retreat. In about 20,000 years' time it is expected that all the northern ice will have melted and that the now temperat zones will be covered with tropical vegetation.

After this temperatures will slowly fall again and ice will begin to pile up in the Arctic. By A.D. 50,000 the ice will probably have moved as far south as the Thames, involving Britain in a new ice age.

Owing to the unreliability of celestial calculations for very early times the astronomical method cannot be reliably applied to the study of periods further back than 600,000 years.

Other studies of the ice ages have given rise to a different and equally impressive method of dating the past. This method is known as *varve analysis.*

During the summer whilst a retreating glacier is melting, a lot of coarse sediment and clay is washed down from it. In certain places the melt water runs into lakes or quiet bays and collects there. The coarse stuff in it soon sinks and accumulates as a layer on the bottom, but currents keep the finer clay particles in suspension.

Not until winter when the melting stops does the water become quiet enough for the clay to settle. This means that every year a double layer of sediment—one of sand and one of mud—is deposited by the glacier. Obviously by counting the number of layers it is possible to get a good idea of how long the glacier has been melting.

These layers, known as varves, are exposed in several parts of the world—Sweden in particular—where lakes have dried out and their beds have been raised up above their original level by earth movements.

Varve studies also yield information about past climates, for the hotter the summer the greater the quantity of water melted and the thicker the layer of sediment deposited. But the reliability of the varve method is restricted to the last 15,000 years or so.

There is an obvious similarity between estimating the ages of rocks by counting varves and estimating the ages of trees by counting their annual rings. The tree-ring method has in fact been used to give detailed information of the seasons during the last 3,000 years.

As in the case of varves the thickness of a tree ring gives a clue to the climate prevailing in the year it was laid down. A series of particularly thin summer rings denotes a drought and so on.

This fact sometimes enables archæologists to date with certainty a beam used in a primitive dwelling. For though the date when the beam was cut is unknown it may be possible to recognise in it a particular series of annual rings which have been dated in other trees growing in the same area and therefore subjected to the same climatic circumstances.

Thus a 1,000-year-old tree felled today may show near its centre a series of six narrow summer rings which were formed as a result of a long drought when it was very young. Other nearby trees which were old at that time and have long since died or been cut would also show the same rings though these would be located near the circumference of their trunks instead of near the centre.

So following recognition of the series in an old beam cut from such a tree it is possible to estimate the time it was cut and so discover when the dwelling containing it was built.

GLOSSARY

ADAPTIVE RADIATION. The progressive splitting off from individuals derived from an unspecialised parent stock of new species better adapted to environments already occupied or adapted to new environments.

AMPHIBIAN. A vertebrate animal typically with four well-developed limbs and characterised by being cold-blooded and aquatic in its juvenile stages of life and air-breathing in its adult stages.

CARBOHYDRATES. Chemical compounds built up of atoms of carbon, hydrogen and oxygen. The hydrogen and oxygen atoms are arranged in the ratio of 2 : 1 as in water (H_2O). Starch, sugar and cellulose are examples.

CELL. A unit mass of protoplasm usually containing a nucleus.

CELL SUBSTANCE. All the living material found within the cell apart from the nucleus.

CELLULOSE. A carbohydrate which makes up the foundation of the cell walls of plants.

CHLOROPHYLL. The green colouring matter which enables plants to make use of the sun's energy in building up foodstuffs.

CHROMOSOME. A string of genes.

CLUB-MOSSES. Primitive plants allied to the ferns.

COLD-BLOODED. Having blood the temperature of which varies with changes in external temperature.

CONVERGENCE. The development of similar characters by organisms belonging to different groups.

COSMIC RAYS. A mysterious form of energy reaching the earth from an unknown source. They are believed to consist of high-energy particles called protons.

CROSSING-OVER. The exchange of parts between the maternal and paternal members of a pair of chromosomes.

CYCADS. Primitive plants related to the conifers but resembling palms or ferns.

DEGENERATION. The return to a simpler condition.

DIFFERENTIATION. The structural modification of tissues which specialises them for particular functions.

DINOSAURS. A group of extinct reptiles which dominated the earth for 160,000,000 years.

DOMINANT GENE. A gene which whilst producing its own effect suppresses the action of the corresponding interchangeable gene. The suppression may be complete or partial.

ELECTRON. The smallest known particle. It is a constituent of all atoms. The chemical nature of an element depends on the number and arrangement of the electrons in its atoms.

ELECTRON-MICROSCOPE. An instrument in which a beam of electrons instead of light is used to magnify an object. Magnifications up to 100,000 times can be obtained with it.

ELEMENT. One of the basic substances of which the universe is formed. There are 93 natural elements. Three others which may have existed naturally ages ago can be made artificially by transmutation.

EMBRYO. A developing organism.

EMBRYOLOGY. The study of the development of embryos.

ENZYMES. Ferments which control chemical actions.

FERTILISATION. The union of the male and female germ cells.

FOSSIL. Anything dug out of the earth which represents the remains of a dead animal or plant.

FRIEDREICH'S ATAXIA. A hereditary disease due to degenerative changes in the nervous system. Chief symptoms are unsteadiness of gait, tremors and curvature of the spine.

GENE COMPLEX. The interacting system formed by all the genes in each cell of an organism.

GENES. The fundamental units of inheritance through which characters are transmitted from one generation to another.

GENUS (PLURAL GENERA). A group of related species.

GERM CELLS. Eggs and sperms in the case of animals: egg cells and pollen grains in the case of plants.

GERM PLASM. The tissue from which germ cells arise.

GINKGOS. Early relatives of coniferous trees. Only one species—the maidenhair tree, widely cultivated as an ornamental plant—has survived.

HÆMOPHILIA. A sex-linked hereditary defect which prevents the normal clotting of the blood.

HETEROZYGOUS. A condition in which the members of a given pair of genes are not alike.

HOMOZYGOUS. A condition in which the members of a given pair of genes are alike.

HORSETAILS. Primitive plants allied to the ferns. Existing examples are small, but many of the fossil horsetails were as large as modern trees.

HUNTINGTON'S CHOREA. A hereditary disease in which paralysis develops at the age of about forty and leads to progressive deterioration of the mental faculties.

HYBRID. The result of crossing two species.

INVERTEBRATE. Without a backbone.

ISOTOPES. Atoms of the same element with the same number of protons and electrons in them but containing different numbers of neutrons. There are about 500 known isotopes of the 96 elements.

LETHAL GENES. Genes which may cause the death of the individuals carrying them.

LINKED GENES. Genes on the same chromosome.

MAMMAL. A vertebrate animal the female of which suckles the young.

MELANISM. Excessive development of dark pigment.

MENDELISM. The theory of breeding ratios developed by Gregor Mendel.

MONGOLIAN IDIOCY. A hereditary condition in which children are born with Mongol-like features and poor mentality.

MUTATION. A permanent change in the nature of a gene resulting in a permanent change in its effect.

NATURAL SELECTION. The process whereby, as a result of the selective influence of the environmental factors, certain individuals of a species survive long enough to reproduce their kind whilst others not so well adapted to these factors perish.

NEUTRON. A particle composing the nuclei of atoms. It has approximately the same mass as a proton but no electric charge.

NUCLEUS. A specialised part of the protoplasm found within all typical cells and composed of chromosomes.

PITUITARY GLAND. A knob of tissue attached to the underside of the brain and producing growth-regulating chemicals.

PLASTICITY. A condition of the gene complex which gives an organism special ability to adapt itself to changed circumstances.

PROTEIN. A complex chemical compound of carbon, oxygen, hydrogen and nitrogen and sometimes containing other atoms.

PROTON. A positively charged particle found in the nuclei of all atoms.

PROTOPLASM. The living substance of an organism.

PROTOZOANS. One-celled organisms.

PURE LINE. A group of organisms within a species so alike as regards their genes that the slight variations between them are due essentially to differences in environment.

RADIOACTIVITY. The production of radiations by the spontaneous breakdown of atomic nuclei.

RECESSIVE GENE. A gene the effect of which is suppressed by another gene.

REDUCTION DIVISION. Cell division at egg and sperm formation to produce cells with only one chromosome of each kind.

REPTILE. A vertebrate animal characterised by being cold-blooded and breathing air throughout its life.

SEDIMENTARY ROCK. A rock formed from fine particles, usually deposited by water.

SEX CHROMOSOME. A chromosome whose special form plays a prominent part in determining sex.

SEX-LINKED GENE. A gene carried on a sex chromosome.

SEXUAL SELECTION. The process whereby, as a result either of physical conflicts or emotional discrimination, certain individuals are favoured as mates to the exclusion of others.

SILICA. Oxide of silicon. Quartz and sand are forms of it.

SOMATIC MUTATIONS. Mutations occurring in the general cells of the body as distinct from those occurring in the germ-plasm.

SPECIES. A group of basically similar individuals the males and females of which can normally breed with one another.

SPONTANEOUS GENERATION. The origin of organisms from inanimate materials.

ULTRA-VIOLET LIGHT. Light waves of short wave-length invisible to the human eye.

VARVE. A layer of sediment deposited by a melting glacier.

VIRUS. A parasite beyond the limit of optical visibility but visible through an electron microscope.

WARM-BLOODED. Having blood which is kept at a fairly constant temperature.

Table I

THE SEVENTEEN AGES OF THE EARTH

No.	Name.	Years since Period Began.	Climate.	Dominant Animals.	Dominant Plants.
17	Recent	20,000	As now	Man and hoofed mammals	Modern Flora
16	Pleistocene	1,000,000	Cool to cold	Man and hoofed mammals	Modern Flora
15	Pliocene	15,000,000	Cool	Hoofed mammals Man emerged	Flowering plants and trees
14	Miocene	35,000,000	Temperate	Mammals Apes emerged	Flowering plants and trees
13	Oligocene	45,000,000	Becoming dry, warmish	Mammals	Flowering plants and trees
12	Eocene	75,000,000	Moderate to warm	Mammals Monkeys emerge	Flowering plants and trees
11	Cretaceous	140,000,000	Warm and moist	Reptiles Small mammals Modern birds	Flowering plants and trees Conifers
10	Jurassic	165,000,000	Warm and moist	Dinosaurs Small mammals Toothed birds	Cycads Conifers Ginkgos

9	TRIASSIC	190,000,000	Warm and dry	Dinosaurs Amphibians Mammals emerge	Cycads Conifers Ginkgos
8	PERMIAN	220,000,000	Moderate then arid and cold	Amphibians Reptiles	Ferns Conifers appear
7	CARBONIFEROUS	280,000,000	Warm and wet then cold	Amphibia Reptiles Insects emerge	Club-mosses Horsetails Ferns
6	DEVONIAN	320,000,000	Warm then probably cold	Fishes Amphibians emerge	Club-mosses Horsetails First land plants
5	SILURIAN	350,000,000	Generally warm	Trilobites Corals, Molluscs Fishes	Seaweeds
4	ORDOVICIAN	420,000,000	Moderate to warm	Trilobites Molluscs First Fishes	Seaweeds
3	CAMBRIAN	550,000,000	Cold to moderate	Trilobites Sponges Molluscs	Seaweeds
2	PRECAMBRIAN	2,000,000,000	Uncertain	Sponges and Protozoa	One-celled plants
1	ARCHÆOZOIC	3,000,000,000	Unknown	Nil	Possibly one-celled plants

TABLE 2

THE EVOLUTION OF THE ANIMAL KINGDOM

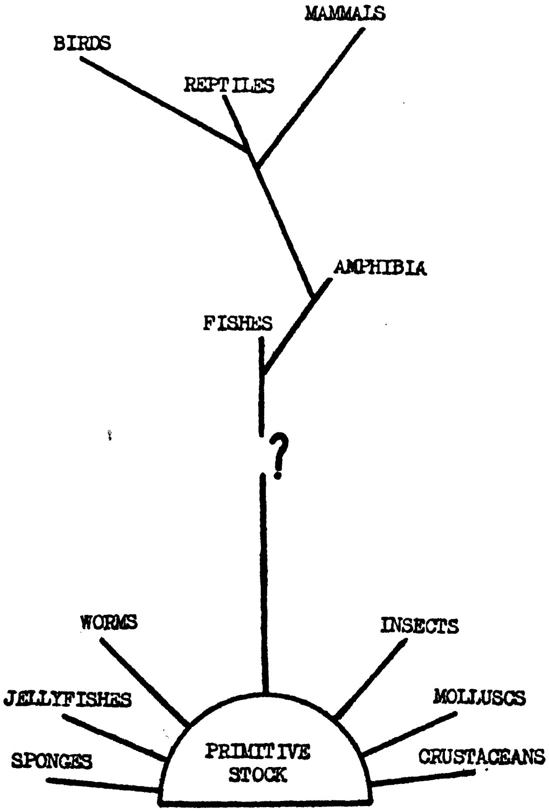


TABLE 3

HOW THE PLANT KINGDOM SEEMS TO HAVE EVOLVED

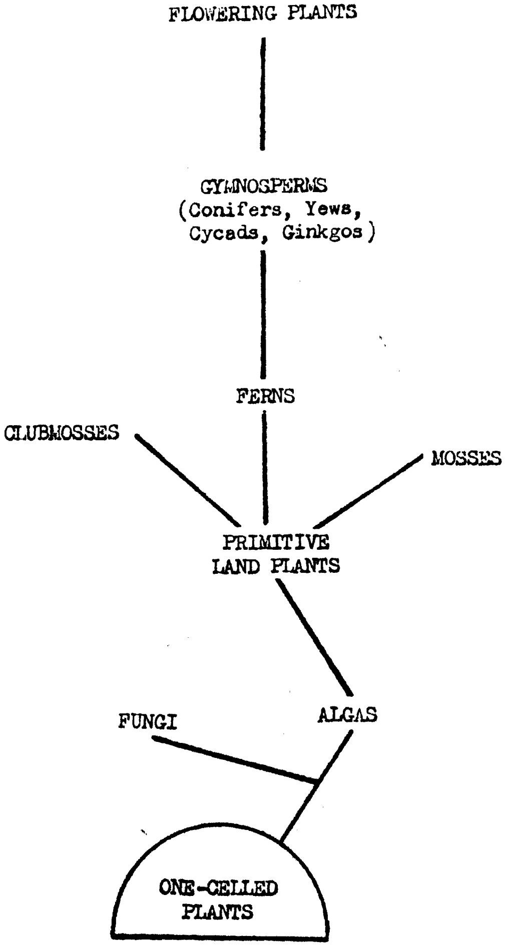


TABLE 4

THE "EVOLUTIONARY TREE" OF THE ANIMALS BASED ON THE EVIDENCE OF FOSSILS

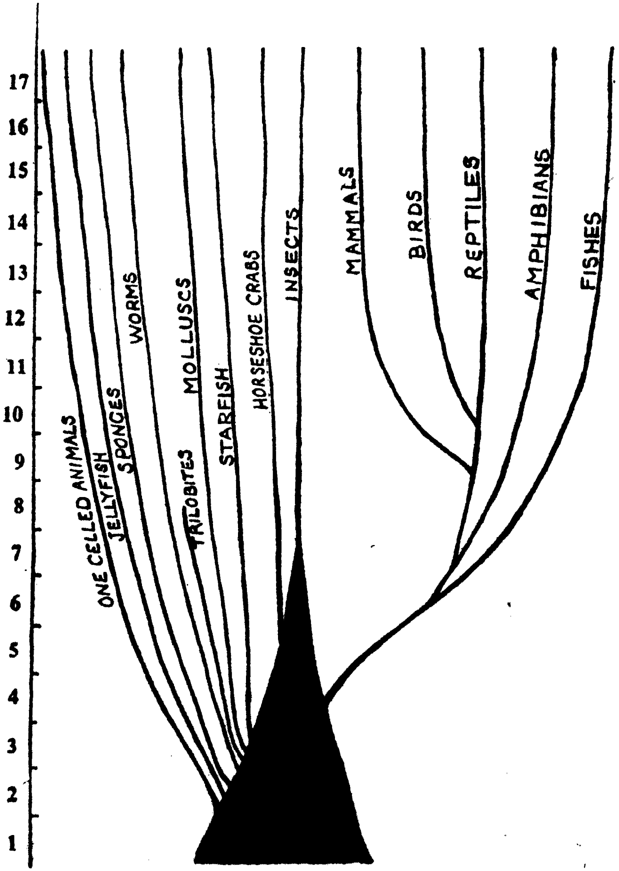
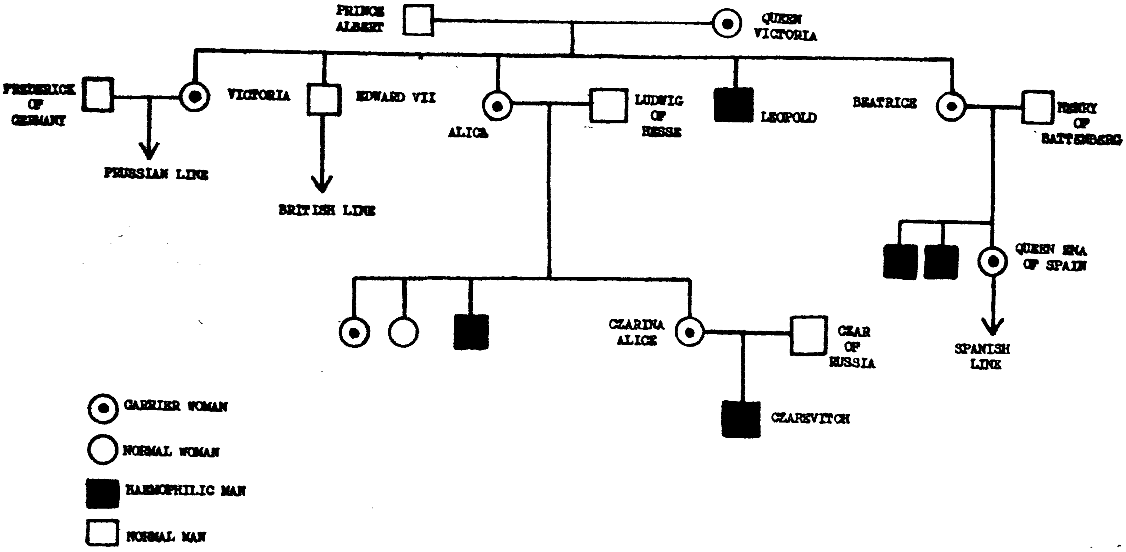


TABLE 5

THE HISTORY OF QUEEN VICTORIA'S HÆMOPHILIA GENE



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INDEX

(*Page numbers in italics indicate illustrations*)

Acquired characters, 120
Adaptive radiation, 159
Algas, 42, 48
Alkaptonuria, 117
Amœba, 32, *33*, 64, 73, *76*, 79
Amphibians, 37, 48, 49, *50*
Amphioxus, *36*, *40*
Ancon sheep, 141
Andalusian fowls, 95, *96*, 141
Apes, 61, 63, 65, 67, 71
Appendix, 63, 162
Archæopteryx, *16*, *55*
Atomic energy, 177
Aurochs, 143

Birds, 38, *40*, 54
Bone-beds, 17
Brain size, 68
Brontosaurus, 19
Brontotherium, *60*
Bushy stunt, 73
Butterflies, 169

Camels, 60
Camouflage, 154
Cats, 60
Cell-division, *82*
Cells, 33
Cheddar Gorge, 71
Chimpanzee, 63, *67*
Chlamydomonas, 41, *42*
Chlorophyll, 42
Chromosomes, 77, *78*, 113, *126*
Cleopatra, 148
Club mosses, 49
Coat colour, in cattle, 100
— —, in rabbits, 106
Cockroach, *34*
Colchicine, 128
Cold-bloodedness, 37
Colour-blindness, 141
Comb-shape, 98, 142
Comet, 148
Comparative anatomy, 61
Conifers, 51
Convergence, 55
Cosmic rays, 140
Crabs, *34*, 156
Cromagnons, 70
Crossing-over, *112*, 127, 155
Crows, *25*
—, distribution, *26*
Cycads, 51
Cynognathus, 59

Dandelions, 124
Dartians, *66*, 67, 71
Darwin, 151
Degeneration, 161
Deluge, 20
Differentiation, 76, 84
Dinosaurs, 52, 166
Diplodocus, *53*, 57
Diplovertebron, *50*
Diprotodon, 158
Dodo, 17
Dogs, 145
Dominance, 92
Drosophila, 113, 134, *136*, 140, 150, 157, 160
Dryopithecus, 67

Ear muscles, *63*
Earth, formation of, 14
Echidna, 58
Egg, human, *77*
Electron microscope, *77*
Electrons, 175
Elephants, 158, 165
Embryology, 64

Environment, 117, 119, 156, 160
Enzymes, 117
Eohippus, 22, *23*, 28
Epihippus, 24, 28
Equus, 24
Erosion, 14
Explosive evolution, 170
Eye-colour, 90, *93*

Ferns, 49
Fertilisation, 81
Fishes, 37, *40*, *47*, 56
Flowering plants, 56
Fraternal twins, 91
Frog, *62*
Fungi, 44

Galapagos Islands, 29
Galeopsis, 128
Gene-complex, 130
Genera, 21
Genes, 77
—, structure of, 115
Genesis, 13, 20
Germ-plasm, 85
Giant chromosomes, *116*
Gigantornis, 61
Giraffes, 121, 151
Glaciers, 184
Gorilla, 63, 65
Grasses, 59

Hæmophilia, 130, 138, 141, *195*
Hair genes, 114
Hawaiian Islands, 30
Heidelberg man, 70
Helium, *175*
Heterozygous genes, 94
Homo, 68, 70
Homozygous genes, 94
Hornless cattle, 93, 125, 140
Horses, 22, *23*, 60
Horseshoe crabs, *47*
Horsetails, 49
Hybrids, 21
Hyracotherium, 28

Ice ages, 61, *183*
Ichthyosaurs, 57
Ictidosaurs, 58
Igneous rocks, 181
Inbreeding, 145
Irish Deer, 157
Isotopes, 179

Jellyfish, 33, 76

Kangaroos, 31, 58
Keith, Sir Arthur, 67
Kelvin, 180

Lamarck, 121
Lamp-shells, 45, *46*
Latimeria, 19
Lead, 178
Lethal genes, *132*
Life, origin of, 73
Lingula, *46*
Linkage, 107
— groups, 110
Lulworth Skipper, 27
Lungfish, *30*

Madagascar, 29
Mammals, 39, *40*, 52, 56
Melanism, 154
Mendel, 95
Mendel's laws, 105
Mesohippus, *23*, 24, 28
Metasequoia, 19
Mice, *132*
Millipedes, 47
Miohippus, 24, 28
Monkeys, 60
Mosasaurs, 57
Moths, 154
Mule, 21
Mutations, 123, 129, 140
—, reverse, 142
—, somatic, 139

Neanderthal man, *70*, 159
Neutrons, 175

Nucleus, 32, *77*

Orohippus, *23*, 24, 28
Ostriches, 60
Ovaries, *80*
Oxygen, 181
Oysters, 149

Paludina, *22*
Parallel evolution, 55
Passenger pigeon, 17
Peas, 99
Pekin-men, 68, *69*
Pigs, 60, 144, 172
Piltdown man, 72, 159
Pithecanthropus, 68
Pituitary, 172
Plasticity, 166
Platypus, 58
Plesiosaurs, 57
Primula, 128, 138
Proconsul, 67
Programme evolution, 157
Protons, 175
Protoplasm, 32
Protozoa, 33, 42
Pterodactyls, *54*
Pure lines, 135

Radioactivity, 177
Recessive genes, 92
Reduction-division, *86*
Reptiles, 38, *40*, 50
Rhamphorhynchus, *54*
Rocks, primal, 14
—, sedimentary, 14

Sacculina, 161
Salenia, 170
Samos, 17
Scurs, 94
Scutosaurus, *51*
Selection, artificial, 145
Selection, natural, 150
—, pressure, 162
—, sexual, 158, 162
Sex chromosomes, *136*
— linkage, 137
Shrimps, *34*
Siamese twins, 91
Special creation, 13
Species, 21
Sperms, 80, *81*
Spiny ant-eater, 58
Spontaneous generation, 20
Stegosaurus, *53*, 54
Stone Age, Old, 71
— —, New, 71
Struggle for existence, 149

Tadpole, *38*
Teeth, *66*
Testicles, 80
Tigon, 21
Titanotheres, 60
Transmutation, 176
Tree-rings, 185
Triceratops, *57*, 58
Trilobites, *45*, 51, 168
Twins, 91, 115
Tyrannosaurus, 53

Uranium, *176*

Varves, 184
Vestigial organs, *63*
Viruses, 73, *74*

Warm-bloodedness, 38, 60
Weeping willow, 139
Whales, 60
Wolves, 60
Wombats, 60
Wookey Hole, 61, 71

X-rays, 123, 140, 142